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DEVELOPMENT OF COAL SLURRY FUELS FOR BLAST FURNACE INJECTION

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DEVELOPMENT OF COAL SLURRY FUELS FOR BLAST FURNACE INJECTION

FINAL REPORT

by

Stelco Inc.

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Objective

In the context of the blast furnace, Stelco's dependence on oil can be reduced by injection of coal-in-oil slurries. Injection of coal-in-tar could further decrease our dependence on oil.

This project developed the economic and technical feasibility of injecting coal slurry fuel into the blast furnace.

Scope

This joint Stelco-Energy Mines and Resources (EMR) program began April 1, 1978. The EMR contract ended December 31, 1979.

- Slurry rheology and stability were studied at R&D during the summer and fall of 1978.
- Slurry pumps were tested at No 2 Open Hearth Utilities Station during the spring of 1979.
- Slurry combustion was studied at the Ontario Research Foundation, Mississauga, during the summer of 1979.
- Hilton Works Engineering provided a preliminary design and capital estimate of a slurry injection facility for 'C' Blast Furnace.
- Facilities Planning provided an economic evaluation of slurry injection at Hilton Works.

Conclusions

1) Slurry injection at Hilton Works is not economic at 1979 fuel prices. The future prices of oil and coal significantly affect slurry injection economics.

2) A 50/50 wt percent slurry of No 6 oil and coal [all of which is finer than 100 mesh (0.0041in)] should perform as well as straight No 6 oil at the blast furnace. For a tar-based slurry, only 30 wt percent of coal is recommended.

3) At 'C' Blast Furnace, a three-tuyere injection trial using the designed on-site coal preparation facility offers more control and flexibility than one having premixed slurry delivered to Hilton Works. The three-tuyere trial would cost from two to three million dollars.

4) For the injection facility, a Worthington Centrifugal Pump and a Worthington Duplex Steam Pump satisfy the pump requirements. Settling in pipelines should not be a problem. Mechanical agitation will be required to prevent coal from settling in storage tanks. Chemical stabilizers are not recommended.

Action

1) **A three-tuyere blast furnace trial cannot be justified at present.**

2) **The Research Department will continue to monitor developments in coal and coal/slurry injection.**

Slurry Combustion Facility at ORF

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INTRODUCTION

The continued well-being of both the Canadian economy and the steel industry requires that we exploit existing energy resources, increase energy efficiency, and develop alternative energy sources. Stelco, in particular, is attempting to reduce its dependence on imported liquid and gaseous fuels.

Injected liquid and gaseous fuels are common blast furnace practice in order to decrease the industry's dependence on expensive metallurgical coke. Fuel injection technology at Stelco is based on natural gas, fuel oil, and coke oven by-product tar (in limited quantities). In the blast furnace, one way to decrease our dependence on portable fuels and simultaneously increase our use of an alternative energy source is to inject coal.

A 1975 state-of-the-art study examined the two known alternatives of employing coal as an auxiliary blast furnace fuel, pneumatic injection of powdered coal and coal-in-oil slurry injection.[1] Following this study, Stelco decided to develop a coal-slurry injection system that would avoid the higher capital and operating costs associated with pneumatic coal injection.

A preliminary investigation of tar-based slurries indicated that acceptable slurry viscosities could not be achieved at high coal concentration, even with coarse coal (minus 10 mesh).[2] The preliminary study indicated the need for a more comprehensive study of coal slurries. This comprehensive study began in April 1978, and was jointly funded by Stelco and by the Federal Government of Canada through the Department of Energy, Mines and Resources (EMR). Our objectives were to determine slurry injection economics and to establish design criteria for a proposed three-tuyere blast furnace trial.

This report summarizes the major findings of the joint Stelco-EMR program to develop coal-slurry fuels for blast furnace injection. Coal-slurry injection economics and slurry combustion are discussed. The report also discusses design criteria for an injection system and provides a preliminary engineering design for a blast furnace injection system.

ECONOMICS

The Facilities Planning Department provided a preliminary economic evaluation of slurry injection at Hilton Works 'C' and 'D' Blast Furnaces.[3] They concluded that slurry injection (50 wt percent coal and 50 wt percent oil) is not economic at 1979 fuel prices. If oil prices escalate faster than coal prices, slurry injection would be economic providing that the capital required is less than seven million dollars.

Future Fuel Prices

The escalation rates used by the Facilities Planning Department are listed in Table I.[3]

Table I: Fuel Price Escalation Factors[3]

Year	Oil and Natural Gas* (%)	Coal** (%)
1980	28	3
1981	25	3
1982	20	7
1983	14	7
1984	13	7
1985	11	7
1986	10	7

* provided by Consumer Gas Company to Marketing Department
** provided by Raw Materials Department

It appears that Canadian oil prices will rapidly escalate in the next few years. It is much more difficult to predict future coal prices. In Canada, we pay world prices for coal, so the escalation in coal prices should not be as great as that for oil prices.

The coal price will be affected by the coal quality required for slurry injection into the blast furnace. At present, it is not possible to set quantitative

specifications for all the coal properties that affect slurry blast furnace injection. A qualitative assessment of coal properties is provided in Appendix I.

Table II shows the effect of escalating prices on the cost spread between oil and several blast furnace fuels.

Table II: Cost Spread Between Alternative Injectants and Oil

Year	Incremental Cost of Oil Over Alternate Fuel ($/ton)		
	Coal	Slurry*	Coke**
1980	62	31	9
1981	92	46	34
1982	119	59	54
1983	142	71	67
1984	164	82	79
1985	185	92	91
1986	207	103	99

* 50 wt % coal
** coke escalated at same rate as coal plus 3%

Figure 1 presents similar information.

Figure 1: Fuel Price Trends

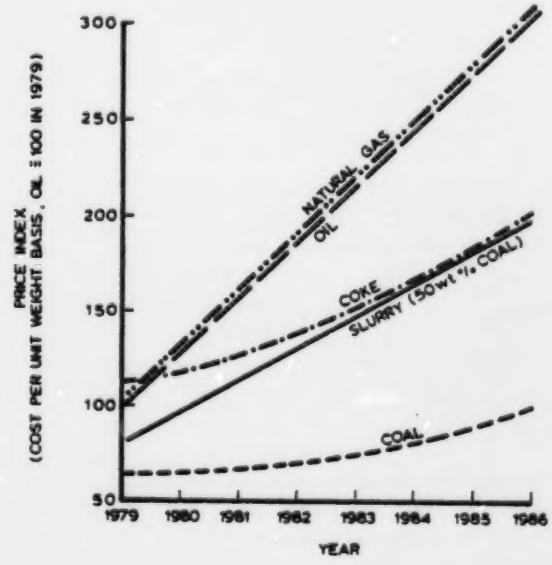


Table II and figure 1 indicate that oil and natural gas will become our most expensive blast furnace fuels. Relative to oil injection, either slurry or powdered coal injection will offer significant savings. (Facilities Planning determined that powdered coal injection would be economic if the capital investment was less than 15 million dollars.[3])

Table II and figure 1 also suggest that oil injection could become unattractive. The oil-coke price differential at which this occurs is difficult to predict since it depends largely upon such factors as coke availability, furnace productivity, and hot metal demand.

There is also a distinct possibility that slurry prices will equal coke prices (1983, considering slurry operating costs). When this occurs, the incentive for slurry injection will be the productivity benefit, associated with injected fuels, relative to a straight coke practice. Considering 1980 oil and coke prices, this is also the major incentive we have for continuing to inject oil.

Relative to a straight coke practice, powdered coal injection would result in lower fuel costs and possible greater blast furnace productivity.[4]

Capital

Even though the oil-coal price spread is greater than the oil-slurry price spread, the economic advantage of the two systems (powdered coal or slurry injection) is similar due to the higher capital cost of a powdered coal system (Table III).

Table III: Slurry and Powdered Coal Injection Economics

Injection Facility	Estimated Capital Cost* ($000)
Slurry	5 000
Powdered Coal	10 000

* Slurry capital cost estimated from single furnace three-tuyere trial capital estimate (see subsequent section, Table II). Powdered coal capital cost provided by Armco.

The capital requirements of a slurry system could be substantially reduced through Federal Government support. This support might allow an acceptable return on Stelco's investment.

Facilities Planning's preliminary economic evaluation indicates that slurry and powdered coal injection merit further consideration. If we proceed with either system, we will be risking capital on the assumption that fuel prices will diverge. This may be an unacceptable risk, considering Stelco's current capital requirements and the possibility of Government intervention (i.e. natural gas will be fixed at 85 percent of the price of oil, Btu basis).

SLURRY COMBUSTION

Slurry combustion studies established the combination of carrier fluid and coal size that would allow maximum coal concentration and yet maintain acceptable combustion behavior. Combustion efficiency decreases as coal size increases and as coal concentration increases. These results agree with recognized combustion theory (Appendix II).

Combustion efficiency also decreases as injection rate increases. This suggests that slurry injection rates will be limited by soot formation in the same manner as oil injection.

From the combustion study we conclude that a slurry of 50 wt percent of minus 100 mesh coal in No 6 oil provides acceptable combustion behavior. Slurries with coarser coal will result in unburnt coal exiting from the raceway. In tar, coal concentration should not exceed 30 wt percent.

Test Facility and Procedures

We contracted the Ontario Research Foundation to design and construct a combustion test facility on their property in Mississauga. The facility (figure 2) simulated actual blast furnace tuyere conditions (650 ft/sec hot blast at 1800°F and 21 percent oxygen).

Figure 2: Slurry Combustion Facility

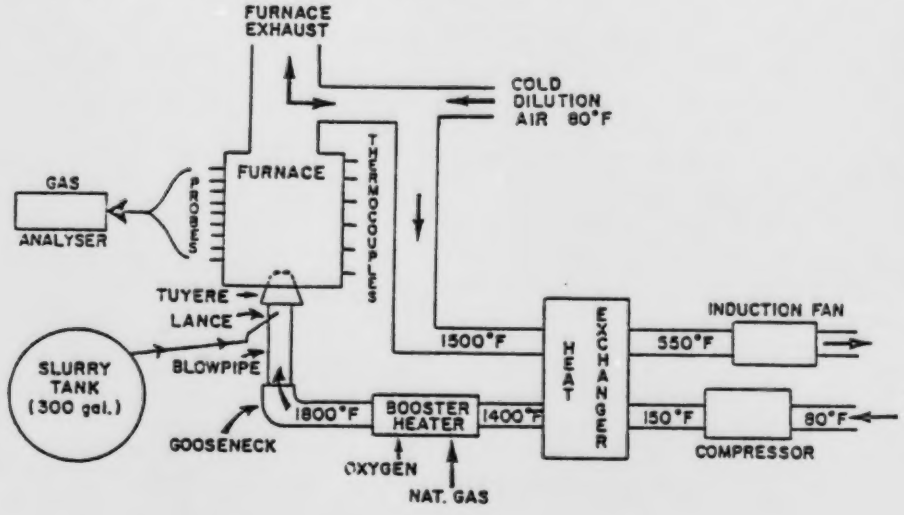
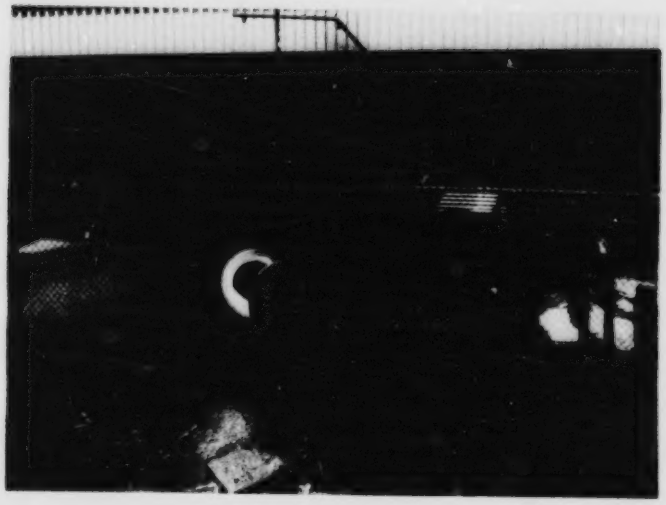


Figure 2 (contd)



A detailed description of the facility and the test procedures is provided in Appendix III.

For the combustion trials, we used three fluid carriers, three coal sizes, four coal concentrations, and two injection rates (Table IV).

Table IV: Slurry Parameters for Combustion Trials

Parameter	Level
Carrier Fluid	Tar; Gulf No 6 Oil (6C); Petrosar No 6 Oil (6P)
Coal Size, mesh	-10; -35; -100
Coal Concentration (wt %)	0; 25; 50; 65
Injection Rate* (lb/min)	4.5; 6

* equivalent 'C' Furnace rates: 135 and 180 lb/NTHM

The combustion test facility was commissioned and the preliminary tests were performed with No 6C oil. No 6P oil and tar were used in the combustion trial program,

since both fluids are available at Hilton Works and they exhibit the greatest difference in viscosity (Table V).

Table V: Liquid Fuels Analysis

Components	Fuel Analysis (%)		
	No 6C Oil	No 6P Oil	Tar
Ultimate Analysis (db):			
Carbon	87.23	86.50	92.47
Hydrogen	10.91	12.43	5.00
Nitrogen	0.33	0.18	0.80
Sulfur	1.36	0.66	0.50
Ash	0.03	0.02	0.16
Oxygen (by diff)	0.14	0.21	1.07
Solids (db)	0.03	0.02	15.99
Moisture (as-received)	0.00	0.35	4.30
Specific Gravity*	0.93	0.87	1.18
Viscosity* (centipoise)	42.5	17.5	57.5

* at 180°F

We expected that the viscosity difference would influence fuel atomization and combustion.

At the start of the program, we evaluated numerous coals. Devco coal met most of our selection criteria (Appendix I). In particular, Devco's low ash (Table VI) and alkali content and its availability make it an excellent coal for blast furnace slurry injection. A full-furnace trial is required to determine if a low ash content justifies a higher coal price.

Table VI: Coal Analysis

Components	Devco Analysis (%)			
	Stockpile	-10 Mesh	-35 Mesh	-100 Mesh
Ultimate Analysis (db):				
Carbon	82.35	81.25	79.26	81.15
Hydrogen	5.56	5.20	4.96	5.25
Nitrogen	1.67	1.48	1.45	1.51
Sulfur	1.27	1.22	1.35	1.13
Ash	3.59	4.60	6.73	4.44
Oxygen (by diff)	5.56	6.25	6.25	6.47
Moisture (inherent)	0.92	1.40	1.44	1.20

The size distributions for the crushed Devco coals used in the combustion trials are given in Table VII.

Table VII: Coal Size Distributions Used for Combustion Trials

Tyler Mesh	Weight Retained on Mesh					
	%	Cum %	%	Cum %	%	Cum %
+10	5.8	5.8				
+20	27.7	33.5				
+35	22.2	55.7	2.5	2.5		
+65	17.3	73.0	35.6	38.1		
+100	7.1	80.1	16.9	55.0	1.3	1.3
+150	3.9	85.0	9.9	64.9	7.9	9.2
+200	5.1	89.1	12.4	77.3	17.9	27.1
+270	2.6	91.7	6.4	83.7	13.7	40.8
-270	8.3	-	16.3	-	59.2	-
Product Designation	-10 mesh		-35 mesh		-100 mesh	

To evaluate slurry combustion we observed the lance plume and furnace exhaust, sampled furnace and exhaust particulates, and analyzed furnace gases.

We sampled particulates inside the furnace and at the furnace exhaust. We did not take exhaust particulate samples for each slurry, nor did we follow a set sampling procedure; nevertheless, the exhaust particulates proved more useful than the furnace particulates. Limitations of the sampling train led to a particulate sampling rate inside the furnace that was below the isokinetic rate. Consequently, we could not use the furnace particulate data for our analysis (Appendix III).

For each slurry, furnace gas composition (CO, CO_2, O_2) was determined along the furnace centerline (assumed to be the flame centerline) at 1 ft intervals downstream of the tuyere. Radial samples, 2.5in, 5in, and 10in from the centerline, were sampled 4 ft downstream of the tuyere. The ratio:

$$\frac{CO_2 \text{ Measured}}{CO_2 \text{ Theoretical}}$$

provided a measure of the degree of combustion. Several factors, particularly plugging of probes, led

us to use only probes 3, 4, and 5 (corresponding to 3, 4, and 5 ft from the tuyere) for the statistical analysis (Appendix III). Paired "t" tests of the CO_2 ratios were used to evaluate the slurries.

We did not use the furnace temperatures to evaluate slurry combustion (Appendix III).

Combustion Results

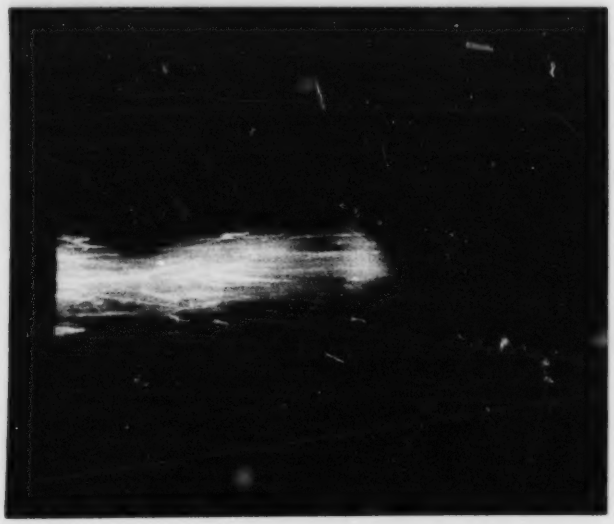
i) Coal Size

The effect of coal size on combustion was evident at the furnace exhaust for all coal sizes and concentrations. Figure 3 illustrates this effect for 25 wt percent slurries of minus 100 and minus 10 mesh coal in tar.

Figure 3: Effect of Coal Size on Combustion

(a) Minus 100 Mesh Coal in Tar

(b) Minus 10 Mesh Coal in Tar



The amount of particulates exhausted from the furnace increased as coal size increased. Analysis of the particulates sampled at the furnace exhaust also shows the effect of coal size (Table VIII).

Table VIII: Effect of Coal Size on Degree of Devolatilization

Coal Size in 50 Wt % Tar Slurry (mesh)	Volatile Matter of Exhaust Particulates (daf, %)
-100	2.4
-35	3.5
-10	6.7

The particulate volatile matter decreases as the slurried coal size decreases. Lower volatile matter suggests more complete combustion.

For slurries of 25 wt percent coal, we could not distinguish a size effect by observing the lance plume; however, for slurries of 50 and 65 wt percent coal, we did see a size effect. At high coal concentrations, the combustion benefit derived from fine coal was confounded by the interaction of coal concentration and size (i.e. viscosity).

Analysis of furnace gas composition (CO_2 ratios) also indicates the effect of coal size on combustion (Table IX).

Table IX: Coal Size Effect on Slurry Combustion

Slurry Coal Concentration (Wt %)	Slurries Compared		Combustion of "A" Significantly Better than "B" (95% Confidence Level)
	A	B	
25	Pure Fluids	-100 mesh Coal	no
	Pure Fluids	-35 mesh Coal	no
	Pure Fluids	-10 mesh Coal	yes
	-100 mesh Coal	-35 mesh Coal	no
	-100 mesh Coal	-10 mesh Coal	yes
	-35 mesh Coal	-10 mesh Coal	yes
50	-100 mesh Coal in No 6P Oil	Pure No 6P Oil	yes
	Pure Fluids	-35 mesh Coal	yes
	Pure Fluids	-10 mesh Coal	yes
	-100 mesh Coal	-35 mesh Coal	yes
	-100 mesh Coal	-10 mesh Coal	yes
	-35 mesh Coal	-10 mesh Coal	yes

At low concentrations (25 wt percent), only combustion of the minus 10 mesh coal slurry is significantly different. For 50 wt percent concentrations, each coal size has a significant effect on slurry combustion.

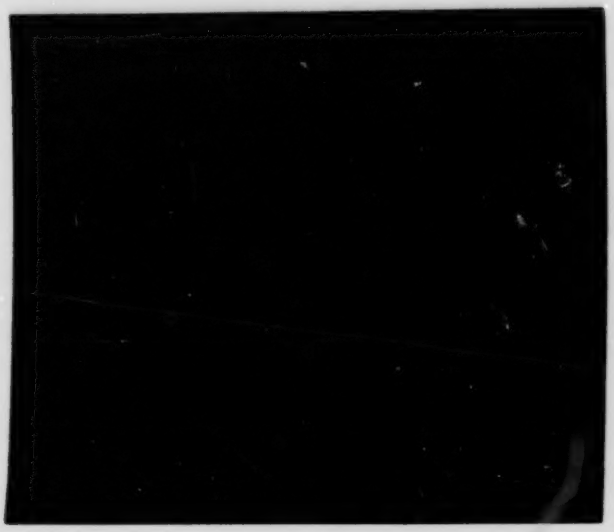
ii) Coal Concentration

The lance plume and furnace exhaust changed dramatically as coal concentration increased. For the minus 10 mesh coal, the darkness (density) of the lance plume decreased as coal concentration increased. At the furnace exhaust, the amount of particulates increased noticeably.

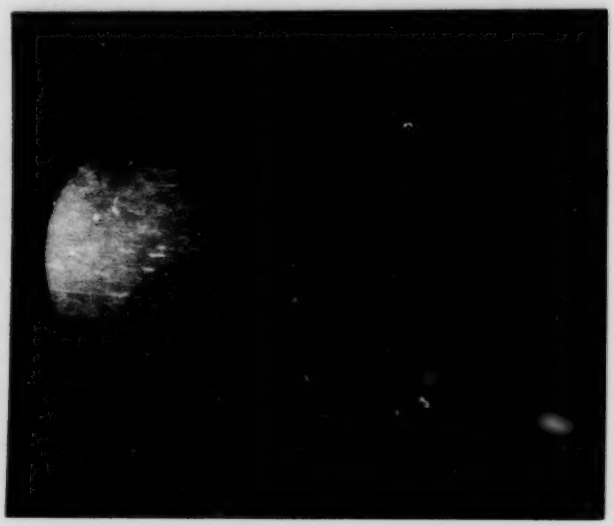
We observed similar effects for the minus 35 mesh coal. For 65 wt percent of minus 35 mesh coal in No 6P oil, the lance plume was very faint (figure 4) and the exhaust was heavily laden with particulates.

Figure 4: 65 Wt % of Minus 35 Mesh Coal in No 6P Oil

(a) Lance Plume



(b) Furnace Exhaust

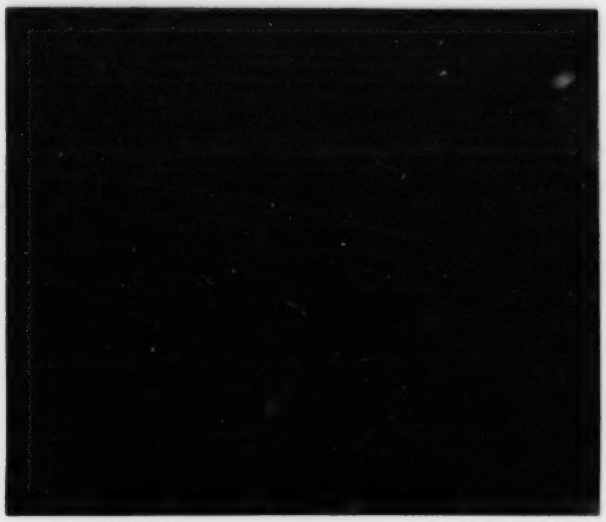


The most dramatic changes in lance plume and furnace exhaust conditions occurred with increasing concentration of minus 100 mesh coal. Figures 5 and 6 show these changes for oil and tar slurries, respectively.

Figure 5: Effect of Coal Concentration on Atomization and Combustion

(a) 25 Wt % Minus 100 Mesh Coal in No 6C Oil

(b) 65 Wt % Minus 100 Mesh Coal in No 6P Oil



(c) 65 Wt % Minus 100 Mesh Coal in No 6P Oil

Figure 6: Effect of Coal Concentration on Atomization and Combustion

(a) 25 Wt % of Minus 100 Mesh Coal in Tar

(b) 25 Wt % of Minus 100 Mesh Coal in Tar

(c) 50 Wt % of Minus 100 Mesh Coal in Tar

(d) 50 Wt % of Minus 100 Mesh Coal in Tar

For up to 50 wt percent of minus 100 mesh coal in No 6P oil, a coal concentration effect was not evident at either the lance plume or the furnace exhaust.* The lance plume was dense and well atomized. Increasing the minus 100 mesh coal concentration from 50 to 65 wt percent resulted in poor atomization (figure 5b) and in significant particulate emission (figure 5c). The exhausting particulates were still burning as they emerged from the furnace.

For minus 100 mesh coal in tar, increasing the coal concentration from 25 to 50 wt percent produced the changes shown in figure 6. At the high coal concentration, there was insufficient slurry atomization, causing slurry to fall onto the inner tuyere surface (figure 6c).

Table X shows the effect of coal concentration on combustion measured by the CO_2 ratios.

Table X: Coal Concentration Effect on Slurry Combustion

Slurries Compared		Combustion of "A" Significantly Better than "B" (95% Confidence Level)
A	B	
25 wt % of -100 mesh Coal 25 wt % of -35 mesh Coal 25 wt % of -10 mesh Coal	50 wt % of -100 mesh Coal 50 wt % of -35 mesh Coal 50 wt % of -10 mesh Coal	yes yes yes
25 wt % Coal 50 wt % Coal	65 wt % Coal 65 wt % Coal	yes no

Clearly, coal concentration significantly affects slurry combustion.

Poor atomization of the 50 and 65 wt percent concentrations is primarily due to the high viscosities of these slurries. Table XI gives the calculated viscosities of several slurries.

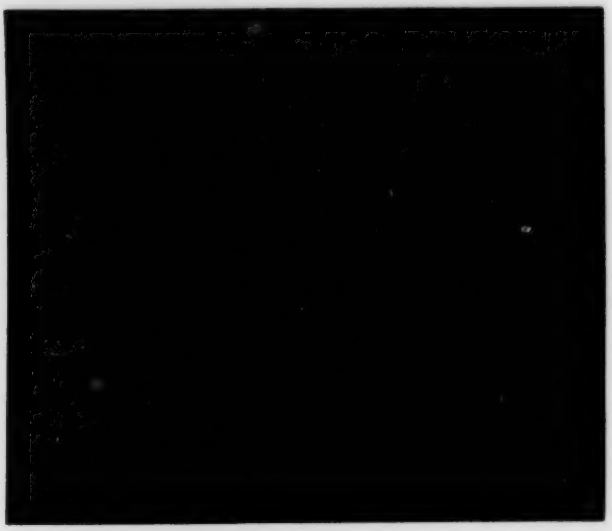
* Photographs of the lance plume or furnace exhaust were not taken at 50 wt percent of minus 100 mesh coal in No 6P oil; however, the furnace exhaust looked identical to the exhaust of the 25 wt percent of minus 100 mesh coal in No 6C oil (figure 5a).

Table XI: Effect of Coal Concentration and Viscosity on Slurry Combustion

Slurry		Viscosity at 180°F (centipoise)	Visual Assessment	
Carrier Fluid	Coal Concentration and Size		Atomization at Lance	Furnace Exhaust
No 6P Oil	50 wt % of -100 mesh	230	excellent	excellent
	65 wt % of -100 mesh	1930	poor	poor
	50 wt % of -35 mesh	160	excellent	poor
	65 wt % of -35 mesh	1010	fair	poor
Tar	25 wt % of -100 mesh	180	excellent	good
	50 wt % of -100 mesh	4580	very poor	poor
	50 wt % of -35 mesh	2780	fair	poor
	50 wt % of -10 mesh	2430	fair	very poor

The 50 wt percent tar slurries of minus 35 and of minus 10 mesh coal have significantly higher viscosities than the slurries of 65 wt percent coal in No 6P oil, yet these tar slurries seemed to atomize as well as or better than No 6P oil-based slurries. The combustion of tar slurries, however, was poor (Table XI and figure 7).

Figure 7: 50 Wt % of Minus 35 Mesh Coal in Tar

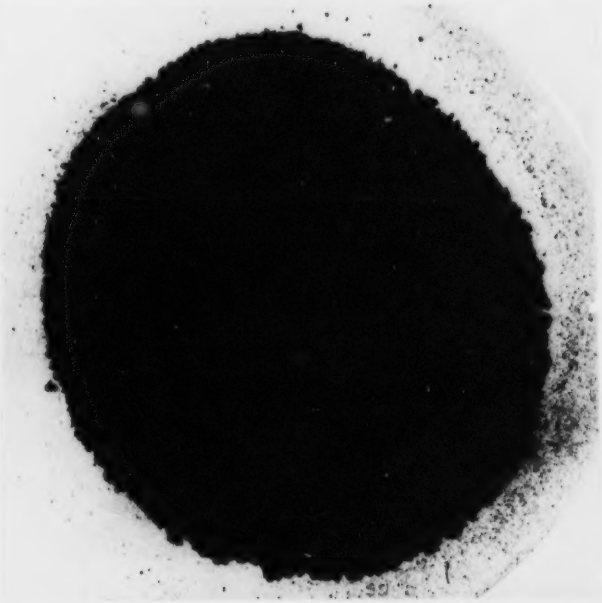


The effect of coal concentration (viscosity) on combustion is also evident from the exhaust particulates. Figure 8 shows these particulates for 50 wt percent tar slurries of minus 100, minus 35 and of minus 10 mesh coals.

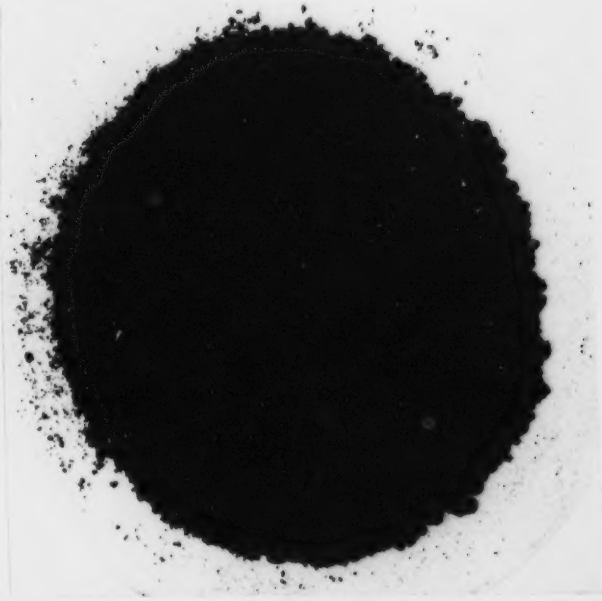
Figure 8: Exhaust Particulates (Actual Size) from Tar Slurries (50 Wt %)

(a) Minus 10 Mesh Coal

(b) Minus 35 Mesh Coal



(c) Minus 100 Mesh Coal



The size of the exhausted particulates should correspond to the injected coal size. This was the case for the minus 10 and minus 35 mesh coals, but not the case for the minus 100 mesh coal (Table XII).

Table XII: Size Analysis of Exhaust Particulates

Tyler Mesh	Particulate Size Distribution (Cum Wt %) for 50% Tar Slurry with Coal Size of		
	-100 Mesh	-35 Mesh	-10 Mesh
+6	0.0	-	5.4
+10	17.1	-	14.1
+20	32.8	0.0	35.7
+35	49.9	13.4	62.9
+65	82.8	84.8	91.9
+100	92.8	96.6	97.0
-100	100.0	100.0	100.0

The large exhaust particulates resulting from the minus 100 mesh coal are a measure of the large droplets that result from poor atomization.

For the 50 wt percent of minus 100 mesh coal in tar slurry, furnace gas analyses suggest excellent slurry combustion, but our visual assessment suggests poor slurry combustion (figure 6 and Table XI). We believe this discrepancy is due to the buildup of slurry on the inside lower surface of the tuyere. This buildup undoubtedly changed the flow pattern of the hot blast. Consequently, we believe that the flame configuration changed, probably shifting the flame centerline. The measured gas compositions assume similar flame configurations (particularly, centerline location) for each slurry. Thus, we did not use the furnace gas composition from the 50 wt percent of minus 100 mesh coal in tar slurry for statistical evaluation (coal size, coal concentration, injection rate, and fluid carrier).

iii) Carrier Fluid

Visually, No 6P oil-based slurries looked better than tar-based slurries for minus 100 mesh coal. For the other two coal sizes, a significant difference was not noted between the two fluid carriers.

Statistical analysis of the furnace gas compositions shows that the fluid carrier is not significant (No 6P oil or tar) at the 95 percent confidence level. At the 90 percent confidence level, the effect of fluid carrier is significant, with tar slurries showing more complete combustion than No 6P oil slurries.

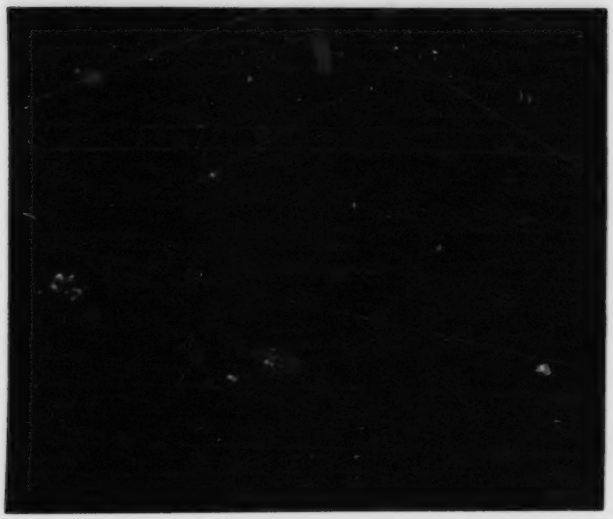
The volatile matter contents of the exhausted particulates also suggest that tar-based slurries combust more completely than No 6P oil-based slurries (Table XIII).

Table XIII: Fluid Carrier Effect on Slurry Combustion

Coal Size for 50 Wt % Slurry	Volatile Matter of Exhaust Particulates (daf, %)	
	No 6P Oil	Tar
-35 mesh	4.1	3.5
-10 mesh	16.8	6.7

These results suggest that tar-based slurries are preferable to No 6P oil-based slurries; however, for the coal size dictated by combustion requirements (i.e. -100 mesh), No 6P oil is the better fluid carrier. At 50 wt percent of minus 100 mesh coal, combustion of the tar slurry was poor. In figure 9, the large dark oval is actually the sampling probe 2 ft downstream of the tuyere. The probe is completely coated by the tar slurry (50 wt percent of minus 100 mesh coal). No other slurry adhered to the probes in this manner. In the blast furnace, such a slurry would not be acceptable.

Figure 9: Tar Slurry (50 Wt % of Minus 100 Mesh Coal) Coating Probe 2 ft from Tuyere Nose



One important factor in the selection of fluid carriers is property consistency. The tar, which we used, had a viscosity of 58 centipoises, a solids content of 16 percent, and a moisture content of 4.3 percent. These properties, particularly the viscosity, are excellent for tar. Since tar viscosities can vary up to 200 centipoises, serious combustion (atomization) problems can occur with tar as a carrier fluid, even at minus 100 mesh coal concentrations as low as 40 wt percent. Thus, for coal concentrations in excess of 30 wt percent, oil (particularly No 6P oil) is preferable to tar.

iv) Injection Rate

For most slurries, we could not visually detect an injection rate effect from the appearance of either the lance plume or the furnace exhaust.

Furnace gas compositions (CO_2 ratios) provide the best indication of the influence of injection rate (Table XIV).

Table XIV: Injection Rate Effect on Slurry Combustion

Injection Rates Compared (lb/min)	Slurry	Combustion at 4.5 lb/min is Better than at 6 lb/min	
		Confidence Level	Significant
4.5 vs 6	Pure No 6P Oil and Pure Tar	87.3	No
	20 wt % of Coal (all sizes) in No 6P Oil or Tar	97.3	Yes
	50 wt % of Coal (all sizes) in No 6P Oil or Tar	99.9	Yes

This table suggests that increasing slurry injection rate will likely have a greater negative effect on combustion than a corresponding increase with a pure fluid. Also, as the coal loading increases, the greater this negative effect will be.

At the blast furnace, slurry injection will be subject to the same limitations as pure fluid injection. Thus, although flame temperature considerations suggest higher injection rates are possible with slurry,[8] combustion considerations suggest equal or lower injection rates are likely.

Operating Problems

We encountered three major problems during the combustion trials. The first problem, failure of the hot blast system, was peculiar to our system and was not related to slurry handling or combustion. The problem occurred midway through the No 6P oil slurry trials and resulted in a three-week delay. When we began again, we renumbered our tests such that all tests numbered in the hundreds were done after the hot blast system was repaired. The hot blast system failed a second time, terminating the slurry trials with four slurry tests remaining.

A second problem, one that could occur at the blast furnace, was coking of the slurry in the lance. This problem did not occur during normal operation; however, on several occasions (for example, when the pump seized, or at the end of a test when the slurry was recycled back to the tank) the slurry coked in the lance before we could purge the system with steam. Coking in the lance occurred if the manual steam purge

was not activated within about fifteen seconds of stopping the slurry flow to the lance. At the blast furnace, with its automatic steam purge, coking of slurry in the lance should not be a problem.

We also had problems with pump seizures and line plugging. These problems occurred with the minus 10 mesh coal and were largely due to poor anchoring of the pump and to very low slurry velocities. These problems will not occur at the blast furnace, because the coal size will be finer, the pumps will be properly mounted, and the slurry velocities will be greater.

Summary

As a result of our combustion trials, we believe that a No 6P oil-based slurry of 50 wt percent of minus 100 mesh coal would be an acceptable blast furnace injectant. We do not expect that higher injection rates will be possible with slurry than with oil.

THREE-TUYERE TRIAL AT 'C' BLAST FURNACE

Hilton Works Engineering prepared a preliminary design of a slurry injection facility for 'C' Blast Furnace.[5] This design was used to estimate the costs of a four-month three-tuyere trial and for the study of slurry injection economics presented in the previous section.

Plant Design and Process Flow

Figure 10 shows the general layout of a slurry injection facility for 'C' Furnace. A detailed list of the major plant hardware is given in Appendix IV.

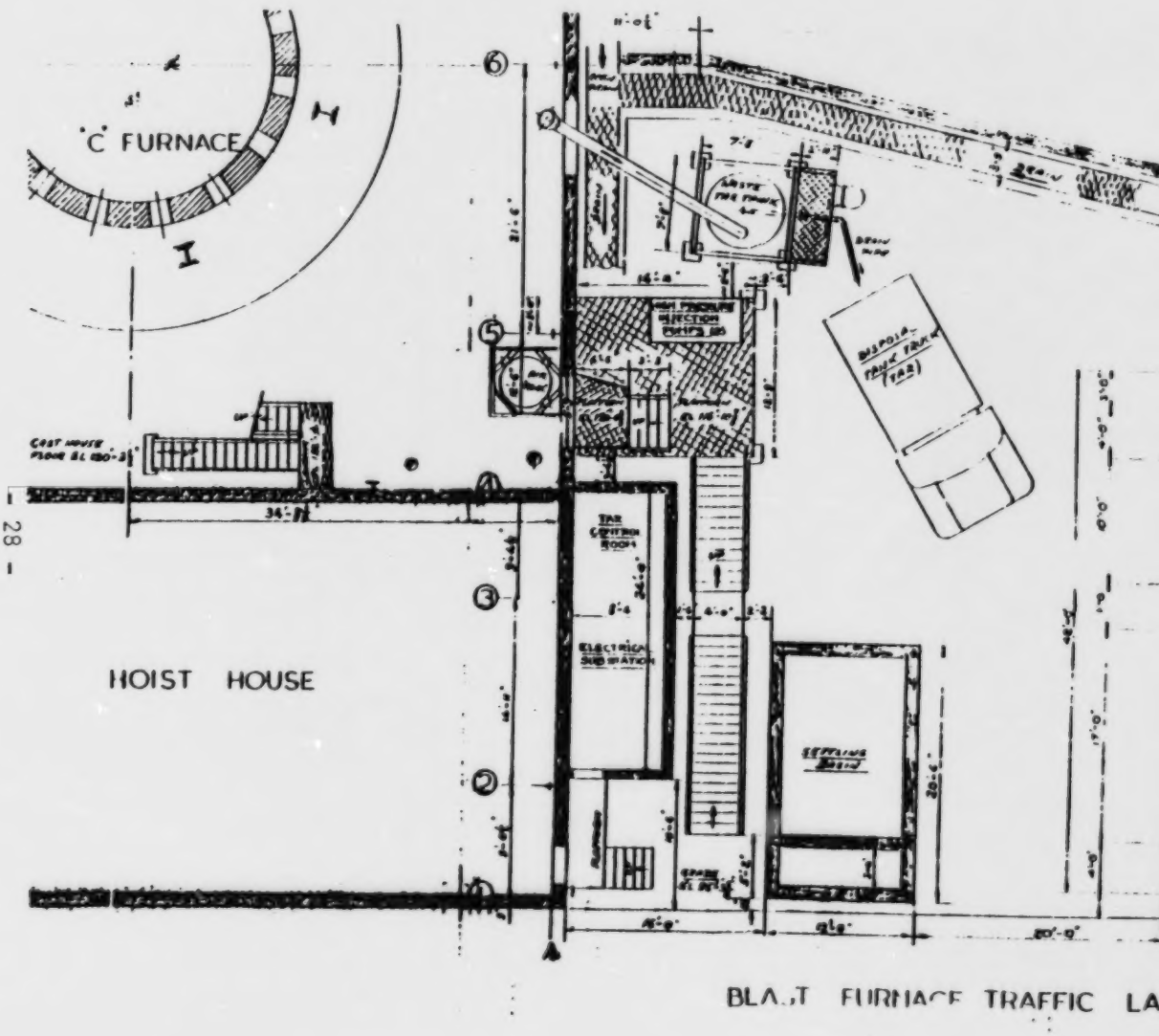
A dump truck transports the coal from the coal piles. At the facility site (located beside 'C' Furnace), the coal is dumped into a storage bin. A front-end loader scoops the coal out of the box and dumps it into a hopper. The hopper dumps onto a conveyor belt which carries the coal up into a feeder to begin the coal processing operation.

The coal is metered into a coal pulverizer which grinds and classifies the coal. Foreign material (iron particles, stone fragments, etc) are separated and rejected down a chute. An internal classifier allows only small coal particles to be carried out of the pulverizer in an "inert" gas stream.

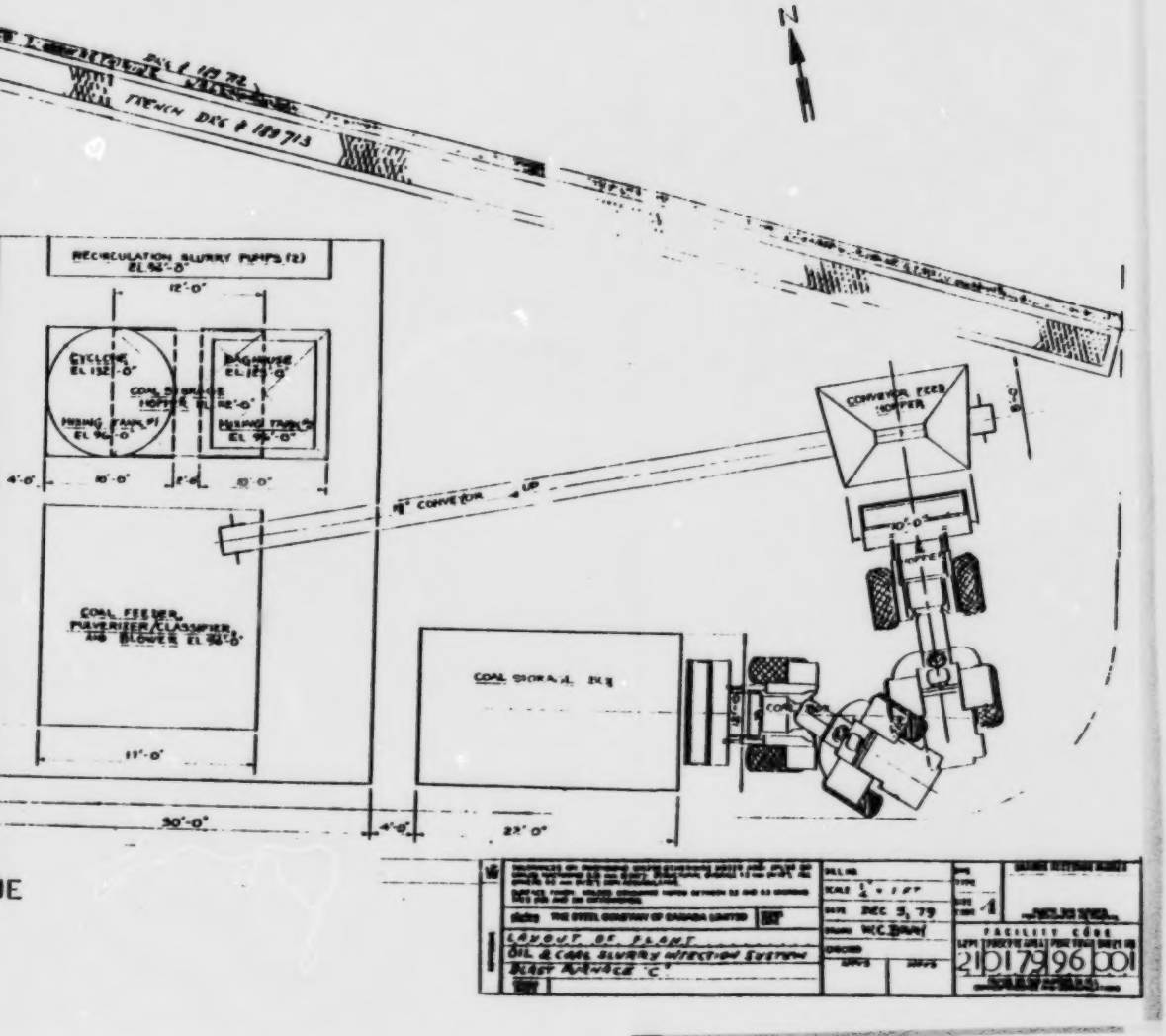
The gas used to carry the coal is air, which is chemically stabilized by depleting the oxygen in a burner flame. This serves the dual purpose of providing a stable carrier gas and increasing the gas temperature to help dry the coal. To reduce fuel consumption, the carrier gas is recycled to the burner where hot combustion gases are added. A portion of the carrier gas is vented to atmosphere through the baghouse. This prevents the accumulation of moisture in the carrier gas.

The coal particles are collected primarily in a cyclone with the remainder filtered out in a baghouse. The cyclone and baghouse hoppers are then dumped into a large storage hopper and the coal is ready for slurry mixing.

Figure 10: Layout of Coal Slurry Facility for 'C' Furnace



SLAG PIT



LAYOUT OF PLANT	SCALE 1/4" = 1'-0"	
OIL & COAL SLURRY INJECTION SYSTEM	DATE DEC 3, 79	
BLAST FURNACE 'C'	DRAWN W.C.	FACILITY CODE 21017996 001
	CHECKED	

JE

The coal particles are transferred from the storage hopper into either of two batch mixing tanks located below the hopper. The quantity added is measured by strain gaged supports on the batch tanks. Fuel oil is piped into the tanks from the 'C' Furnace fuel oil system. The oil is weighed in a similar fashion to the coal. The tanks are sealed with a gas vent from the lid to the baghouse. The coal is slurried with the oil by a paddled mixer. The slurry is heated by a steam coil to reduce viscosity.

The slurry is pumped from either tank bottom around a recirculating pipe loop. This ensures a steady flow of homogeneous slurry. One pump is capable of moving the slurry. A second pump (in parallel with the first) is kept on standby.

The slurry is tapped off the pipe loop into a high pressure pump. The slurry is then forced through the injection lances into the furnace.

When the blast furnace operation is interrupted, the pipelines are all purged by steam and drain either into the furnace or back into the slurry tanks. This practice will prevent carburization in the furnace lances and "freezing" in the feed loop.

The coal treatment, slurrying, and injection processes are controlled from the tar control room located on the side of the 'C' Furnace hoist house adjacent to the coal-slurry facility.

Facility and Operating Cost

For the three-tuyere trial, we investigated the possibility of having a premixed slurry (prepared off-site by Allied Oil) delivered to Hilton Works instead of preparing the slurry at 'C' Furnace. A premixed slurry eliminates the need for the coal preparation facility (coal storage and conveyor system, grinder, baghouse, drier) and would substantially reduce the cost of a three-tuyere trial (Table XV).

Table XV: Three-Tuyere Trial Cost Estimate

Major Cost Item	Cost ($000)	
	Slurry Prepared On-Site	Premixed Slurry Delivered to Site
Capital*	1520	320
Operating:		
Slurry	330	760
Labor	900	800
Rentals	100	0
Total	2850	1880

* order of magnitude capital estimate supplied by Works Engineering[7]

Allied Oil (Cleveland, Ohio) seems to be the only supplier of slurry (720 000 US gallons for a four-month trial). They will have a one million US gallons per month facility operating by the summer of 1980.[6] The cost of delivered slurry (Table XV) includes purchase at Cleveland and trucking to Hilton Works. The disadvantages of using a delivered slurry are that we would:

- be exposed to uncontrolled coal and oil sources,
- not gain experience in operating a coal preparation facility, and
- still require an on-site coal preparation facility for a subsequent full-furnace (all tuyere) trial.

A three-tuyere trial using the designed on-site coal preparation facility offers more control and flexibility. Also, this facility could supply sufficient slurry for a full-furnace trial.

SLURRY INJECTION SYSTEM

To aid Engineering in the design of a slurry injection system, we tested candidate slurry pumps and flow meters. We also studied slurry rheology and slurry stability to provide design criteria for the injection system.

Slurry Pumps

A blast furnace slurry injection system requires two types of pump: a high-volume low-pressure pump for circulation, and a high-pressure pump for injection into the blast furnace.

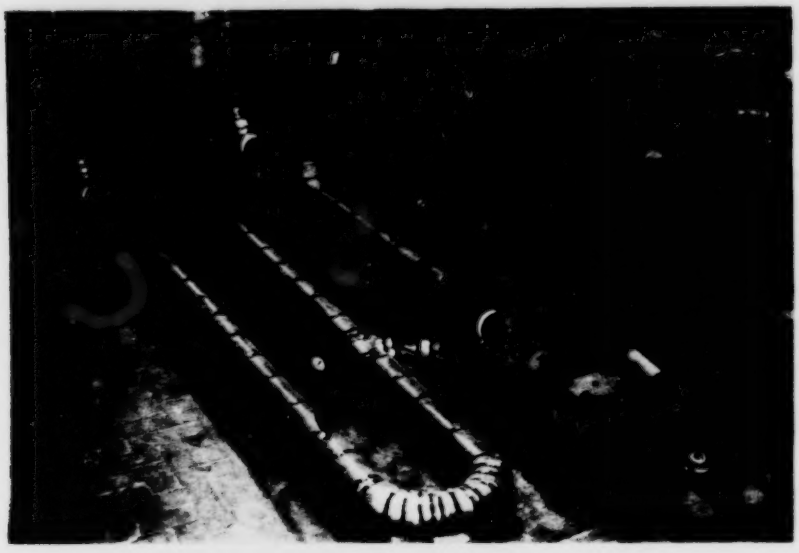
Stelco Engineering recommended two pumps for a coal-slurry injection system at Stelco and designed a test facility to test the selected pumps in coal-slurry service. The pump selection criteria are described in Appendix V.

A Worthington "Type M" Centrifugal Slurry Pump and a Worthington Horizontal Duplex Steam Pump are suitable for slurry recirculation and injection, respectively. The centrifugal pump should last at least two years before it requires maintenance for wear. The steam pump will have more serious wear problems, probably requiring annual servicing. Leaking seals on both pumps presented problems during the trials and will require regular servicing if used in a blast furnace facility.

The Worthington Centrifual slurry pumps have been used successfully at Stelco's By-Product Plant and Central Boiler Station for the pumping of tar. Steam-operated Duplex pumps, similar to the Worthington Duplex steam pump, have been used for transferring tar at Stelco for over 30 years.

The test facility consisted of a holding tank and mixer to prepare the slurry and keep the coal in suspension. The centrifugal pump loop delivered slurry to the duplex piston pump and/or returned slurry to the holding tank (figure 11). The Duplex Piston pump pumped the slurry through a lance back into the holding tank. Details of the pumping trial are given in Appendix V.

Figure 11: Pump Test Facility (Prior to Service)



We ran the test facility continuously. The centrifugal pump operated for approximately 2020 hours. The steam pump operated for approximately 1840 hours.

We used a Moyno pump for our slurry testing and combustion trials. This pump is also discussed in Appendix V.

i) Worthington
Centrifugal
Pump

The Worthington "Type M" Slurry Pump, Model 2-1/2 M091-N1 Hard (figure 12), is a single-stage end-suction centrifugal pump designed for pumping slurries and abrasive mixtures.

Figure 12: Worthington Centrifugal Pump

This pump was able to pump a slurry of 50 wt percent coal in No 6C oil. Wear in pump components should not be a problem during extended service. The pump was able to handle slurries with viscosities well in excess of 1000 centipoises.

Water leakage is a potential problem. Small water leaks into a slurry fuel injection system are tolerable but not desirable. Flushing with oil instead of water or adoption of a new seal design are possible solutions. Worthington of Canada recognizes that flushing leakage can be a problem with this model and are currently developing seals with extremely low leakage rates.

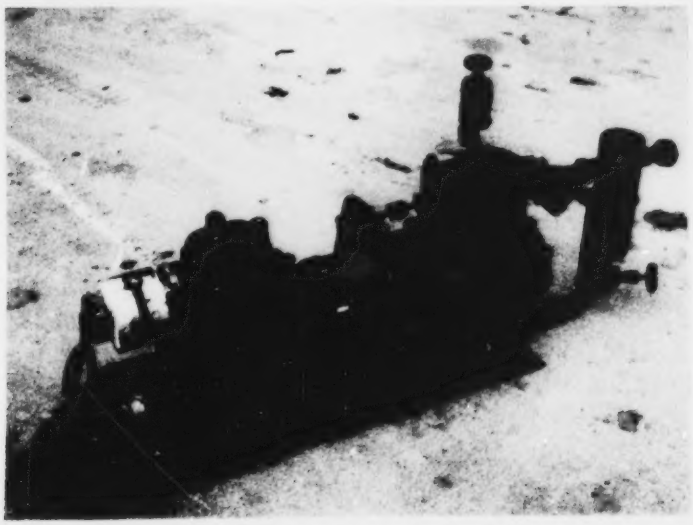
Another problem encountered during the trial was slurry leaking into the seal flushing water drain. This would occur on a slurry injection system if the flushing pressure became too low. For our test facility, this leakage was due to bay water sediment fouling a needle valve.

During the trial the slurry became thicker and more viscous. The slurry viscosity became significantly greater than the desired trial viscosity of 1000 centipoises, yet the pump continued to perform (Appendix V).

ii) Worthington
Horizontal Duplex
Piston Steam
Pump

The Worthington Horizontal Duplex Piston Steam Pump, figure 13, consists essentially of two single pumps arranged side by side.

Figure 13: Worthington Duplex Steam Pump

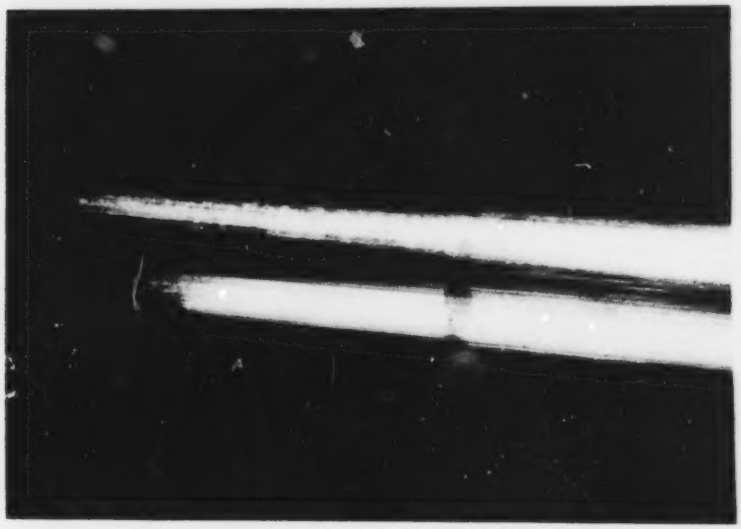


At the end of the trial, after 1842 hours of slurry service, the slurry end of the Duplex pump was dismantled and examined for wear (Appendix V).

The Worthington Horizontal Duplex Piston Steam Pump, Model 4-1/2 x 2-3/4 x 4 VC with modified stainless steel disc valves and hardened stainless steel cylinders, was able to pump 50 wt percent coal in No 6C oil. The pump should perform for approximately one year before maintenance is required to replace worn internal parts.

During the pumping trials the two slurry stuffing boxes leaked excessively. A new packing ring was required every few days and the gland required tightening several times in each 24-hour period. Examination of the piston rods at the end of the trial revealed scoring in the area where the rods passed through the stuffing box (figure 14).

Figure 14: Scored Piston Rod



This explains the difficulty in keeping a seal and indicates the need for piston rods made from a more wear-resistant steel for slurry service.

The leaking seal problem emphasized the need for mounting this pump with catch basins and with adequate access to the slurry stuffing boxes for maintenance.

Slurry Metering

Four slurry flow meters were used over our wide range of slurry conditions. A load cell metering system was the most useful; however, it is suitable only with a batch injection system. A Micro Motion Mass Flow Meter would be suitable for a continuous injection system.

i) Load Cell
Metering

The load cell system was useful for batching the various slurries as well as for metering the slurry feed rate. A load cell metering system is included in the design of the three-tuyere injection facility.

Each leg of the slurry feed tank was mounted on a load cell. The signals from the three load cells were processed and displayed by two digital indicators.

The mass flow indicator displayed the slurry mass feed rate in pounds per minute. The load cell signals were sampled at 4-minute, 32-second intervals; the mass flow rate was computed and displayed. Mixing tank vibration, caused by the slurry agitator, led to instantaneous fluctuations from the combined load cell signals. At the low flow rates used for the combustion trials (4.5 and 6 lb/min), these fluctuations resulted in indications of significant flow rate changes by the mass flow indicator, although the flow rate remained constant.

Thus, the mass flow indicator was not used to meter the slurry feed rate. The accuracy of the mass flow indicator would improve with greater flow rates or with decreased tank vibration.

The weight in/weight out indicator provided a continuous display of either the weight of slurry in the tank (weight in) or the cumulative weight of slurry removed from the tank (weight out). We computed the mass flow rate by recording either display (usually the weight out) at known time intervals. This procedure was, in effect, a duplication of the mass flow meter function. To overcome the problem of tank vibration and fluctuating load cell output, we allowed the display to stabilize by stopping the agitator approximately 7 seconds prior to recording the displayed weight out.

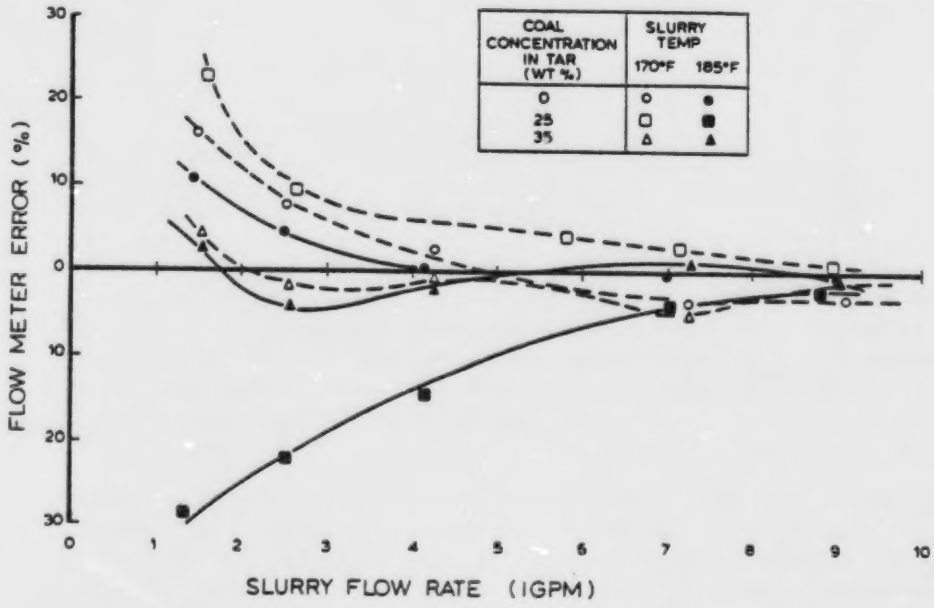
ii) Micro Motion
Mass Flow Meter

This meter, supplied by Micro Motion Incorporated, measures mass flow directly. The meter was tested with slurries of minus 35 mesh coal in No 6C oil, No 6P oil, and tar. The meter was rated for a flow range of 0 to 400 lb/min. At our maximum flow rates

(approximately 100 lb/min), we were operating at 25 percent of full range. Calibration was done at our high flow rates. As the flow rate decreased, the error in metered flow rate increased. Also, for the same calibration setting, the error in metered flow increased as coal concentration increased. For the tar-based slurries, the meter gave erratic results and could not be zeroed.

Since we were operating at the low range of the meter, it is not surprising that the error in metered flow increased as flow rate decreased. At flow rates from 60 to 100 lb/min, the error in measured flow became constant. For the No 6P oil-based slurries, this error was about 1 percent (the meter was calibrated for each coal concentration up to 60 wt percent. For the No 6C oil-based slurries, the error increased from about 2 percent for the pure fluid to 12 percent for the 60 wt percent slurry (the meter was calibrated only once using the pure fluid). For the tar-based slurries the error was about 4 percent (the meter was calibrated only once using pure tar; slurries up to 40 wt percent were used at 170 and 185°F, figure 15).

Figure 15: Micro Motion Flow Meter Performance



In addition to measuring mass flow, the meter measured slurry specific gravity. A measure of specific gravity would be very useful in an injection system. Unfortunately, the meter was precise to only 0.1 units, which covers a wide coal concentration range; nevertheless, our data suggests that this function operated properly.

iii) Ultrasonic
Flow Metering

Neither of the two ultrasonic meters was satisfactory for metering slurries over the wide range of conditions used in the viscosity trials.

A Controlotron Corporation ultrasonic flow meter was tested with slurries of minus 10 mesh coal at concentrations up to 30 percent. With increasing coal concentration, a greater positive deviation from actual volumetric flow measurements was observed. This deviation was partially explained by a positive reading during the absence of flow; however, readjustment of the calibration controls could not compensate for this drift.

This meter is used by Stelco to control oil flow to two blast furnaces; however, we feel it is not suited for slurries with high coal concentrations.

An NP Industries Incorporated ultrasonic doppler flow meter was tested with slurries of minus 10 mesh coal at concentrations up to 60 percent. This meter could accurately monitor flow only over a narrow velocity range (±1 ft/sec). Outside this range the response was nonlinear. When we calibrated the meter at our high flow rates (4 to 5 ft/sec), high readings were registered for lower flow rates (compared to volumetric flow measurements). There was, however, no incremental pattern to the abnormal readings. Also, the meter required recalibration as the coal concentration increased.

Problems also occurred when the slurry temperature exceeded 180°F. At this temperature the amplitude of the transmitted high frequency signal dropped, indicating reduced signal strength from the transducer. This reduction shifted the calibration point. This particular problem can be corrected with high temperature transducers.

Slurry Rheology

We studied slurry rheology primarily to establish empirical relationships that could be used to design a slurry injection system. In particular, we wished to develop a simple model for predicting slurry viscosities over a broad range of slurry conditions: coal size (Table XVI), coal concentration, fluid type, and slurry temperature (Table XVII).

Table XVI: Devco Size Distributions Used for Viscosity Trials

Tyler Mesh	Coal Retained on Tyler Mesh					
	%	Cum %	%	Cum %	%	Cum %
+10	10.4	10.4				
+20	20.4	30.8				
+35	24.3	55.1	0.2	0.2		
+65	17.8	72 9	37.4	37.6		
+100					5.3	5.3
+150	12.1	85.0	29.1	66.7	9.7	15.0
+200					11.5	26.5
+270	6.4	91.4	14.3	81.0	6.0	32.5
-270	8.6	100.0	18.9	100.0	67.5	100.0
Product Designation	-10 mesh		-35 mesh		-100 mesh	

Table XVII: Carrier Fluids and Test Temperatures

Fluid	Temperature (°F)	
	Low	High
Tar	170	185
No 6C Oil	160	185
No 6P Oil	120	170

We used a test loop (Appendix VI) to determine slurry viscosities. A detailed discussion of the theory, analysis, and results is presented in Appendix VI.

i) Test Results

Curvilinear regression analysis of the viscosity data produced equation 1 as a correlation between dimensionless kinematic viscosity and coal concentration:

$$\ell n \left(\frac{\nu}{\nu_o}\right) = \ell n\, A + B_n\, C^2 \qquad .....(1)$$

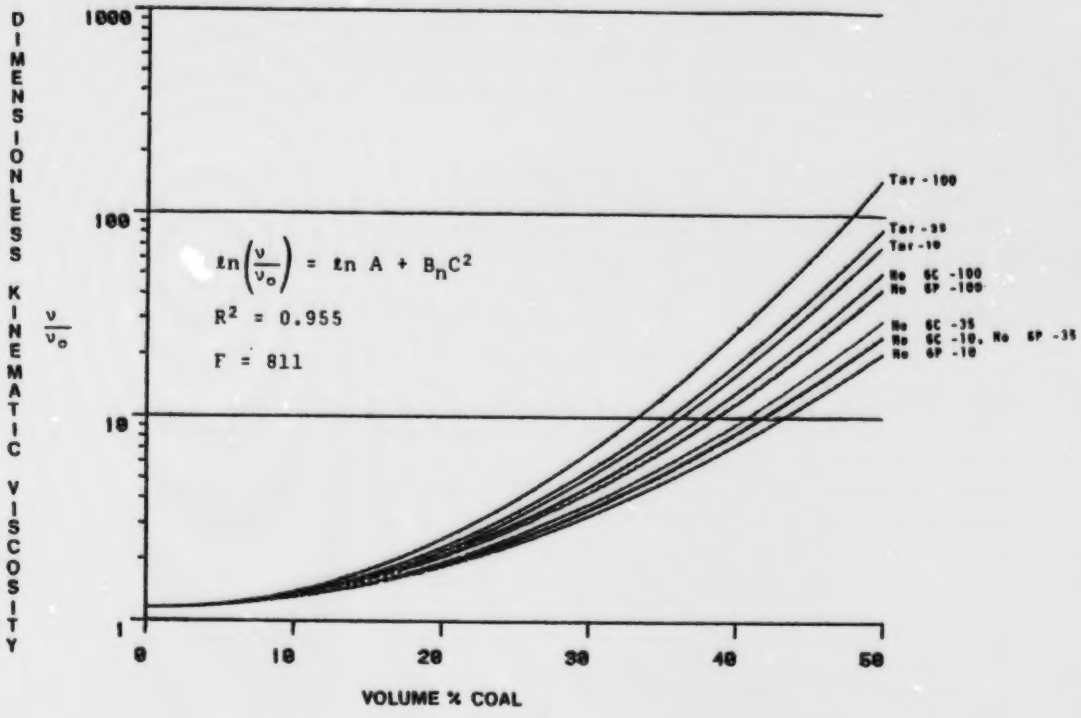
where: ν = slurry kinematic viscosity at temperature T
ν_o = carrier fluid kinematic viscosity at temperature T
A = intercept (1.1584)
C = coal concentration, volume %
B_n is the coefficient for specific combinations of coal size and of carrier fluid (Table XVIII).

Table XVIII: B_n Values ($\times 10^4$)

Carrier Fluid	Coal Size (mesh)		
	-10	-35	-100
Tar	16.45	17.24	19.41
No 6C Oil	12.25	13.03	15.21
No 6P Oil	11.51	12.30	14.47

Equation 1 is presented graphically in figure 16.

Figure 16: Slurry Viscosity



Our results indicate that, for each fluid carrier, slurry viscosity increases as coal concentration increases and as coal size decreases. These two results were expected.

Unfortunately, our results indicate that carrier fluid type also affects slurry viscosity. We did not study the fluids to determine why they affect slurry viscosity. Undoubtedly, much of the effect lies in the different fluid structures. Tar is primarily a long chain aromatic fluid, and No 6P oil is a ring paraffinic fluid.

A major difference between tar and the two oils is that tar has a high initial concentration of solids (up to 25 percent). Our results show that concentration has an exponential effect on viscosity. Thus, tar-based slurries would be expected to show a more pronounced viscosity:concentration relationship than the oils.

Equation 1 has no temperature coefficient. Temperature, of course, does affect viscosity, but using a dimensionless viscosity normalizes the temperature effect. To use equation 1, the carrier fluid initial viscosity, ν_o, must be known at the slurry operating temperature.

Since equation 1 was developed to predict slurry viscosity, its limitations should be noted. Of course, slurries with different coal size consists or of different carrier fluids might fall outside the range of equation 1. The use of coals of different rank (i.e., lignites) may also produce significant errors.

The presence of water, either as coal surface moisture (our coal had approximately 3 percent moisture) or as free or emulsified water will result in higher viscosities than predicted by the equation. This moisture effect might be a problem with tar-based slurries, since tar moisture can vary substantially (our tar had approximately 7 percent moisture).

Even though the effect of temperature is compensated for by the carrier fluid initial viscosity, slurries at very high (above 220°F) or very low (below 100°F) temperatures might have viscosities significantly different than predicted by the equation.

Equation 1 is more complex than we had anticipated. Nevertheless, we feel that it can be used to predict the viscosities of slurries suited to blast furnace injection.

Slurry Stability

We studied the settling of slurried coal to determine the effects of carrier fluid, coal concentration, and coal size on slurry stability. We also tested several chemical additives designed to prevent coal from settling.

Slurry stability increases (coal settling decreases) as fluid carrier specific gravity and viscosity increase, as coal concentration increases, and as coal size decreases. The chemical stabilizers that we tested did not suspend coal coarser than 65 mesh. A water-in-oil emulsion was as effective as the chemical stabilizers.

Our procedure for studying slurry stability is detailed in Appendix VII. Basically, our technique involved recording the weight gain as coal settled from a slurry (180°F) onto a pan suspended from a load cell.

i) Fluid Carrier

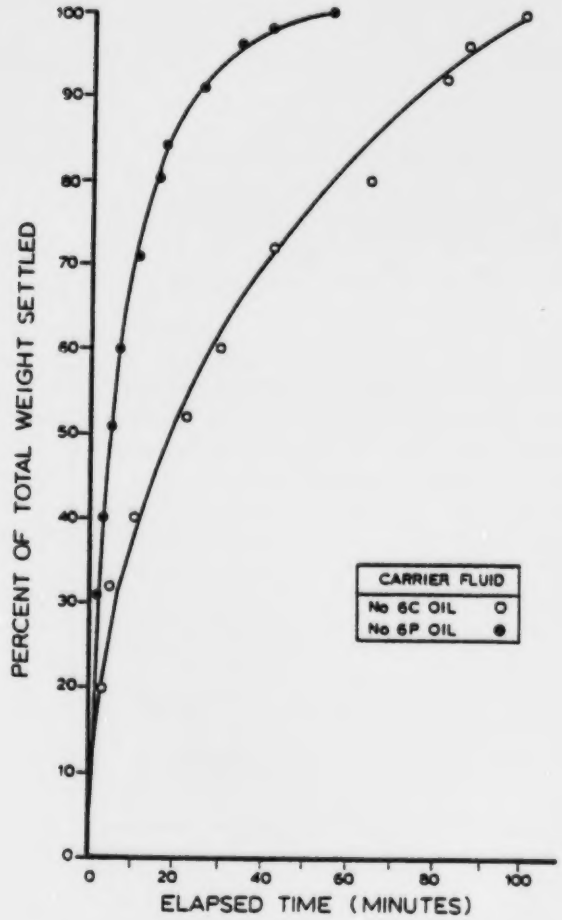
The effect of fluid carrier on slurry stability was established for No 6C oil, No 6P oil, and tar. For 40 wt percent slurries of minus 10 mesh coal (Table XIX), slurry stability increases when the fluid carrier changes from No 6P oil to No 6C oil, or to tar.

Table XIX: Devco Size Analysis (Stability Tests)

Tyler Mesh	Size Analysis	
	Weight %	Cumulative %
+10	5.6	5.6
+20	16.4	22.0
+35	24.0	46.0
+65	20.6	66.6
+150	15.0	81.6
+270	7.4	89.0
-270	11.0	100.0

Figure 17 illustrates that No 6C oil-based slurries are more stable than No 6P oil-based slurries.

Figure 17: Slurry Stability (40 wt % Coal)



With our apparatus, we did not detect settling of a 40 wt percent minus 10 mesh coal in tar slurry; however, beaker tests revealed settling does occur. We cannot explain why we did not detect settling in the tar slurry with our apparatus.

Stokes Law (equation 2) predicts that settling velocity decreases as fluid specific gravity and fluid viscosity increase.[8]

$$V = \frac{g(\rho_s - \rho_f)D}{18\mu} \qquad .....(2)$$

where: V = terminal settling velocity of particle
g = acceleration due to gravity
ρ_s = solid specific gravity
ρ_f = fluid specific gravity
D = particle diameter
μ = fluid viscosity

For our carrier fluids (properties listed in Table XX), Stokes Law predicts that stability should increase (settling decrease) as the fluid carrier changes from No 6P oil to No 6C oil to tar.

Table XX: Carrier Fluid Properties at 180°F

Carrier Fluid	Specific Gravity	Viscosity (centipoise)
No 6C Oil	0.90	17
No 6P Oil	0.86	54
Tar	1.20	174

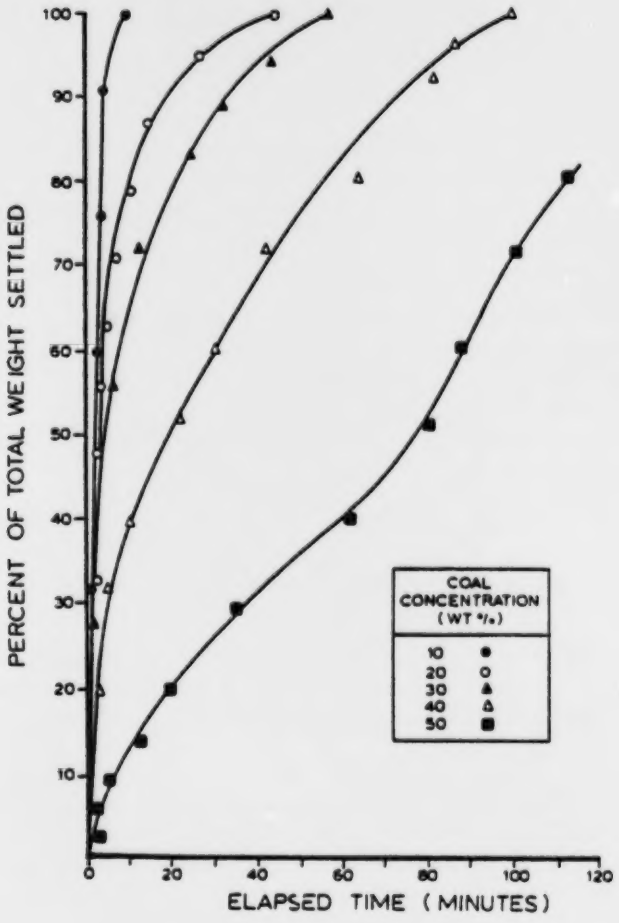
Stokes Law applies only to a single particle settling in a fluid; however, the effect of fluid properties should be similar for any number of settling particles.

Chemical interaction between coal and the carrier fluid can also affect slurry stability. This interaction between coal and tar should be greater than that between coal and No 6C oil because the more complex tar contains more compounds that would react with coal particles. Thus, tar slurries should be more stable than oil slurries for both physical and chemical reasons.

ii) Coal Concentration

The influence of coal concentration on slurry stability is shown in figure 18. As coal concentration increases, slurry stability increases (settling decreases).

Figure 18: Stability of No 6C Oil-Based Slurries



The increased stability at higher coal concentrations occurs because the frequency of particle-particle collisions increases and each collision slows down the settling particles.[10] Also, the very fine particles and the fluid carrier become, in effect, a homogeneous fluid relative to the coarse coal particles. The specific gravity and viscosity of this homogeneous fluid are greater relative to the carrier fluid, thereby reducing the settling rate of the coarse coal (as predicted by Stokes Law).

iii) Coal Size

The distribution of particles settling in a 40 wt percent minus 10 mesh coal in No 6C slurry was determined. After one hour of settling we removed a slurry sample from the top half of the settling pan. We extracted the coal from the sample (Appendix VII), sized the coal, and compared the sized coal to the initial size distribution.

We found that essentially all coal coarser than 65 mesh settled, and that the proportion of suspended coal increased as the coal particle size decreased (Table XXI).

Table XXI: Size Analysis of Suspended Coal

Tyler Mesh	Before Settling	After Settling
+65	66.6	0.2
+150	15.0	1.1
+270	7.4	16.6
-270	11.0	82.1

iv) Chemical Stabilizers

We determined the effect of various chemical additives (Table XXII) and emulsified water on the stability of a 40 wt percent of minus 10 mesh coal in No 6C slurry.

Table XXII: Stabilizers Tested

Manufacturer	Product
Quaker City	Non-Ionic SCA Cat-Ionic SCB
Drew Chemical	Amergy 5200
Alchem	BX 1797
-	Water-in-Oil Emulsion

The chemicals were evaluated by comparing the settling (figure 19) and the size distributions (Table XXIII) of the coal suspended in the top half of the settling pan.

Figure 19: Effect of Chemical Stabilizers

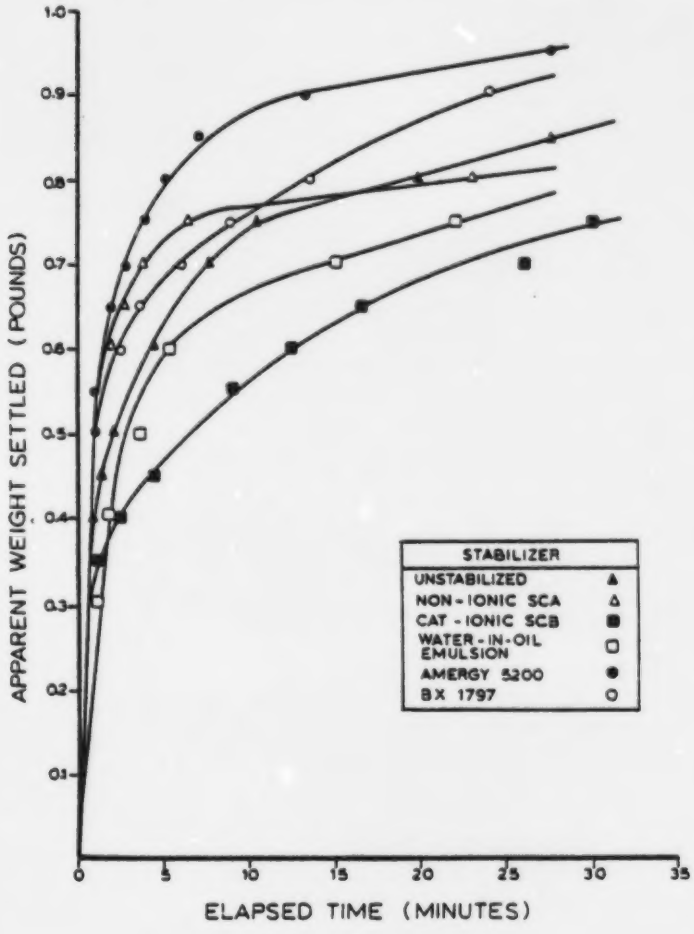


Table XXIII: Size Analysis of Suspended Coal in Stabilized Slurries

Tyler Mesh	Before Settling	After Settling						
		Unstabilized		Non-Ionic SCA	Cat-Ionic SCB	Amergy 5200	Water-in-Oil Emulsion	BX 1797
		No 1	No 2					
+65	66.6	0.2	0.2	3.7	0.1	0.5	0.2	0.4
+150	15.0	1.4	0.8	29.7	6.5	5.0	2.9	2.3
+270	7.4	17.6	15.6	25.9	23.6	24.6	29.5	20.4
-270	11.0	80.8	83.4	40.7	69.8	69.9	67.4	76.9

Figure 19 shows that the stabilizers vary in effectiveness once the coarse coal has settled (after the first few minutes). Relative to the unstabilized slurry, the Cat-Ionic SCB and the water emulsion appear to improve stability (reduce settling). The BX 1797, the Non-Ionic SCA, and the Amergy 5200 appear to reduce stability (increase settling).

Table XXIII suggests that each stabilizer improved stability (suspended coarser coal) relative to the unstabilized slurry; however, only the Non-Ionic SCA was significantly better than both the unstabilized slurry and the other stabilized slurries. Table XXIII suggests that the stabilizers we tested cannot suspend coal coarser than 65 mesh.

We do not recommend the use of chemical stabilizers, even though our results suggest that they might improve the stability of fine coal slurries (-150 mesh). The stabilizers are not completely effective, so agitation is still required. Also, since stabilizers function through surface chemistry at the coal-oil or coal-oil-water interface, changes in any of these components (coal rank, coal source, oil source, bay water chemistry) can change the effectiveness of the stabilizers.

v) Settling in
Slurry Pipelines

During the combustion trials, slurries of minus 35 mesh and minus 100 mesh coal in No 6P oil at concentrations up to 65 wt percent were pumped for time periods up to 7 hours through a 5 ft length of lin pipe at flow velocities of 0.2 and 0.3 ft/sec. The line did not plug. When we pumped slurries of minus 10 mesh coal the pump seized because the line plugged. By modifying our slurry feed system, we increased our flow rates to 0.9 and 1.2 ft/sec. This reduced, but did not eliminate, the plugging problem with the minus 10 mesh coal.

In view of our experience in mixing and pumping slurries of minus 35 mesh and minus 100 mesh coal, we feel that slurry stability will not be a problem with a slurry injection system using fine coal.

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APPENDIX I

COAL CHARACTERISTICS FOR SLURRY INJECTION

The quality of coal required for blast furnace injection will vary from one steel company to another. This is particularly true when we consider the acceptable levels of properties, such as coal ash, alkali, and sulfur content. Nevertheless, the following discussion should apply, in general, to all blast furnaces.

Specific Coal Characteristics

i) Coal Alkali Content

Coal alkali ($Na_2O + K_2O$) content is an important criterion. Blast furnace alkali loading, in excess of 6 lb/NTHM, has a serious effect on blast furnace performance, causing rough operation, scaffolding, and even premature furnace shutdowns.[11]

Since the liquid carriers contain no alkalis, replacing them with coal increases blast furnace alkali loading. This undesirable consequence must be minimized by using a coal with very low alkali levels. Candidate coals for slurry injection should have alkali levels less than 0.1 percent. If slurry injection rates exceed present auxiliary fuel injection limits then additional coke will be replaced. The coke alkali level is then the determining factor, along with the replacement ratio of the slurry, relative to coke.

ii) Coal Ash Content

Coal ash has several undesirable effects on coal slurries. The ash is more dense than the carbon; thus, at high ash levels, the coal particle density increases and coal slurry stability decreases. Also, coals with higher ash levels are generally harder to grind and are more abrasive. An ash increase would probably increase grinding costs and equipment wear.

Coal ash will also influence blast furnace operation. Slag volumes have to be increased to handle the added ash and extra flux has to be added to maintain minimum slag basicity. The penalties, in terms of blast furnace performance are:[8]

$$\text{+1 lb/NTHM of slag volume} \equiv \text{+0.25 lb/NTHM of coke consumed} \qquad \text{.....(1 AI)}$$

and

$$\text{+1 lb/NTHM of raw flux} \equiv \text{+0.15 lb/NTHM of coke consumed} \qquad \text{.....(2 AI)}$$

Armco uses a pulverized coal injection system and has empirically determined the following relationship:[12]

$$\frac{\text{lb coke replaced}}{\text{lb coal injected}} = 1.48 - 0.666 \frac{\text{\% coal ash}}{\text{\% coke ash}} \qquad \text{.....(3 AI)}$$

This relationship indicates that low ash coals are desirable. It may not, however, relate to slurry injection nor to the effect of coal ash on the replacement of oil. Nevertheless, it is the best available indicator for assessing the potential effect of coal ash on blast furnace operation.

Since carrier fluids have no ash, the ash loading/NTHM to the blast furnace will increase when slurry is used. As with alkali loading, this undesirable increase must be minimized by using a low ash coal. The quantity of coke replaced is again a determining factor in assessing the maximum acceptable ash level.

iii) Coal Sulfur Content

The coal sulfur content is not as critical as ash or alkali content. The penalties incurred at the blast furnace are not as severe for sulfur as they are for alkalis or ash. Generally, the adverse effects would involve an increase in slag basicity, which may necessitate the use of more flux, an increase in slag volume, or external hot metal desulfurization.[8]

The allowable sulfur content of the coal will depend on the choice of carrier fluid. At current injection levels, the slurry sulfur content should not exceed the carrier fluid sulfur content. If coke is replaced beyond this limit by injecting more slurry, the slurry sulfur content should be no greater than the coke sulfur level. The higher the injection level, the more severe the restraint on sulfur becomes.

iv) Coal Moisture Content

The role of water in coal slurries is not fully understood. Water improves slurry stability when it is emulsified with the oil. Also, water is often required to enhance the stability provided by special chemical stabilizers.

Emulsified water in a slurry droplet rapidly volatilizes during combustion. The rapid volume expansion of the gas creates an explosive situation that improves combustion efficiency by increasing atomization and by preventing agglomeration of the coal particles.[13] It is doubtful that coal surface moisture is as effective as emulsified water.

Water, in the form of steam, is often used to maintain smooth blast furnace operation. Unfortunately, a coke penalty of approximately 3.8 lb/NTHM is incurred for each grain of moisture added per cubic foot of wind blown.[8] Moisture in the coal slurry would be expected to have a similar negative effect on coke rate.

Slurry moisture, acting similar to blast moisture, will lower the raceway adiabatic flame temperature.[8] Since an acceptable flame temperature level must be maintained the amount of slurry that can be injected will be reduced if coal moisture contents are high.

v) Coal Grindability

For slurry pumping and injection, it will be necessary to grind the coal. The critical factor affecting coal size preparation is its grindability or softness. This property influences grinding energy requirements, mill wear, and even mill size or capacity. As coal grindability increases, it is our experience that lower capital and operating costs can be achieved.

Table I AI shows that softer coals (higher grindability) generally have a greater proportion of fines in the as-received condition than do the harder coals.

Table I AI: Delivered Coal Size

Coal		Hardgrove Grindability Index	Minus 100 Mesh Size Fraction (%)
Designation	Rank (Bituminous)		
A	low-volatile	95	14
B	low-volatile	98	12
C	medium-volatile	99	12
D	medium-volatile	81	11
E	high-volatile	69	9
F	high-volatile	61	3

If, for example, 100 mesh was the top coal size allowed for our application, then only 86 percent of coal A would have to be ground compared to 97 percent of coal F. Thus, softer coals would cost less to prepare than hard coals for coal slurries. To a certain extent, coal mining and coal beneficiation techniques also affect the delivered size distribution.

Grindability increases in the order: coke, anthracite, lignite, subbituminous, bituminous high-volatile, bituminous medium-volatile, and bituminous low-volatile. Grindability is affected by coal ash content, petrographic composition, coal weathering, and oxidation. These factors can produce significant variations in coal grindability within any coal mix. In general, bituminous coals are preferable.

vi) Carbon/Hydrogen Ratio

The C/H ratio is often cited as a measure of the quantity (lb/NTHM) of a fuel that can be injected into the blast furnace. In general, the higher the C/H ratio, the greater is the amount of fuel that can be injected.[8] The C/H ratios of various potential injectants are listed in Table II AI.

Table II AI: Representative Fuel C/H Ratio

Fuel	C/H
Coke	200
Anthracite	30
Low-Volatile Coal	19
Coal Tar	18
Creosote	17
Medium-Volatile Coal	17
High-Volatile Coal	15
Subbituminous Coal	10
No 6C Oil	8
No 6P Oil	7
Natural Gas	3

The coal-slurry C/H ratio depends on the coal and oil selected and on the ratio of coal to oil. On the basis of C/H ratio, it should be possible to inject more coal slurry than the oil presently used. The hydrogen associated with slurry moisture has the same effect as the chemically bound hydrogen in the fuel.

vii) Coal Specific Gravity

Specific gravity is not a critical coal property. In general, coal specific gravity decreases as coal rank decreases. The low rank coals have lower specific gravities because they have high porosity and volatile matter content. The specific gravity range for most coals is from 1.25 to 1.45.

A coal with low specific gravity is desirable since it will not settle as rapidly as a coal with high specific gravity. On the other hand, for equal weight concentration, a greater volume of the lower specific gravity coal is required. The increased volume results in higher slurry viscosity and higher pumping costs per unit weight of slurry.[9]

Coal rank may, therefore, have an indirect influence on slurry viscosity. If acceptable stability can be maintained, then the highest coal specific gravity is desirable. This criterion suggests the use of bituminous or anthracite coal.

viii) Ash
Composition

With the exception of alkali content and, in rare cases, phosphorus content, coal ash composition is not critical in blast furnace use. It is possible, however, to specify an ideal ash composition that is compatible with the ironmaking and steelmaking processes. This composition is given in Table III AI.

Table III AI: Ideal Coal Ash Composition

Component	Content
Alkalis (Na_2O, K_2O)	min
Phosphorus (P_2O_5)	min
Sulfur (SO_3)	min
Acids (SiO_2, Al_2O_3)	min
Bases (CaO, MgO)	max
Iron (Fe_2O_3)	max

ix) Combustion

Petrographic composition influences coal combustion properties. Reactive components, such as vitrinite, readily combust, whereas inert components, such as fusinite, require long residence times for complete combustion.[14] Oxidized coal is also difficult to combust.

For blast furnace injection, the coal and liquid fuel must combust in the tuyere zone, the only place where oxygen is available. At present, it is not known whether coal reactivity is critical for complete combustion in the tuyere zone of a blast furnace. To avoid incomplete combustion, a coal with a low inert content should be used.

Coal Selection for Slurry Fuel Development Program

The coal selection criteria discussed in the previous section were used to evaluate candidate coals for slurry injection. Detailed analyses of coking coals were available from previous studies. Coke breeze,

anthracite, subbituminous, and lignite coal were also considered. The data for these latter fuels were not as complete as for the coking coals.

Devco coal was selected as the most suitable coal for slurry injection. Devco's properties are compared to coking and noncoking coals in Table IV AI.

Table IV AI: Suitability of Devco Coal

Selection Criteria	Suitability of Devco Compared to	
	Coking Coals	Noncoking Coals
Alkali Content	excellent	excellent
Ash Content	excellent	excellent
Purchase Price	above average	poor
Availability	average	average
Sulfur Content	poor	average
Grindability	below average	average
C/H Ratio	poor	average
Moisture Content	average	above average
Petrographic Composition	excellent	above average
Ash Composition	excellent	excellent
Specific Gravity	excellent	above average

Although quantitative weighting of the selection criteria was not done, alkali content, ash content, purchase price, and availability were deemed the most critical. In qualitative terms, the importance of the various selection criteria is indicated from the groupings of Table IV AI.

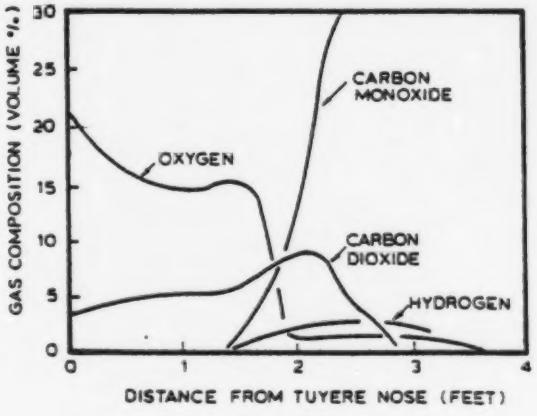
Ideally, a noncoking coal should be used for slurry injection, thereby conserving coking coals.

APPENDIX II

COMBUSTION THEORY

In the blast furnace, the injected fuel must be converted to CO or CO_2 before the coke in the raceway consumes all the available blast oxygen (figure 1 AII).[15] Too long a combustion time results in incomplete combustion, thus decreasing combustion efficiency and increasing soot formation through cracking of the vaporized carbon.

Figure 1 AII: Raceway Gas Composition Without Fuel Injection



For a blast velocity of 650 ft/sec, injected fuel has approximately 6×10^{-3} seconds to combust (1.5 ft inside the tuyere and 2 ft in the raceway, figure 1 AII). Blast velocity decreases in the raceway, giving the fuel more time to combust than it would have for a constant 650 ft/sec blast.

The time required for complete combustion of a liquid droplet is given by:

$$t \equiv \frac{D^2}{\lambda_\ell} \qquad \text{.....(1 AII)}$$

where: D is the droplet diameter
λ_ℓ is the liquid "burning constant" which varies for each liquid

For a solid particle, the time for complete combustion is given by:

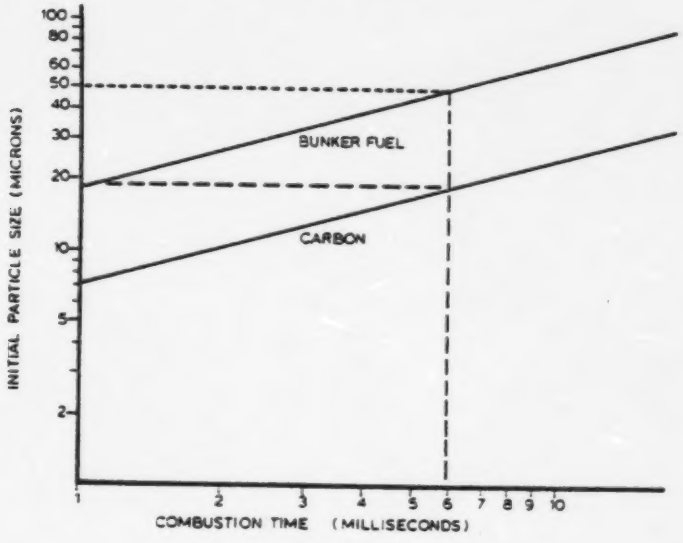
$$t \equiv \frac{D^2}{\lambda_s} \qquad \text{.....(2 AII)}$$

where: D is the particle diameter
λ_s is the solid "burning constant" which varies for each solid

In general, solid combustion time is longer than liquid combustion time by a factor of about 13.[16] Thus, slurries with their solid coal particles will take longer to combust than pure fluids. Also, since slurries have higher viscosities, a slurry (comprised of coal and liquid) will not atomize as well as a pure liquid, thus increasing combustion time still further.

Figure 2 AII[15] shows the relationship between fuel particle size and combustion time for solid carbon and for Bunker fuel.

Figure 2 AII: Combustion Time of Solid and Liquid Particles



To completely combust within 6 x 10^{-3} seconds, a No 6C fuel must be atomized to 50 microns or less. Solid carbon must be less than 20 microns in diameter. For

coal combustion, the combustion time:particle size line lies between the carbon and No 6C fuel lines of figure 2 AII. The coal line approaches the No 6C fuel line as coal volatile matter increases.[16] Many other factors, such as coal ash content (ash has a negative effect since it prevents diffusion of gases), coal reactivity, and coal moisture content affect coal combustion.

Thus for slurries, combustion efficiency should decrease as coal size and coal concentration increase.

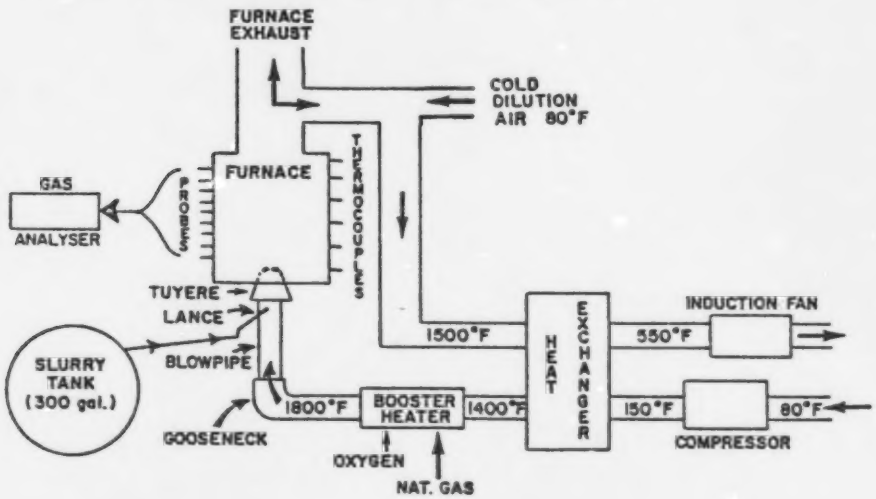
APPENDIX III

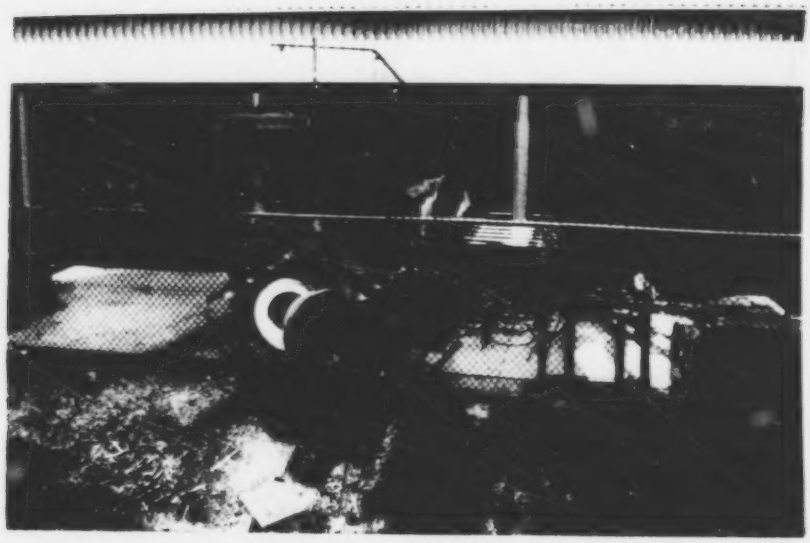
SLURRY COMBUSTION

Test Facility

We contracted the Ontario Research Foundation to design and construct a combustion test facility on their property in Mississauga. The facility (figure 1 AIII) simulated actual blast furnace tuyere conditions (650 ft/sec hot blast at 1800°F and 21 percent oxygen).

Figure 1 AIII: Slurry Combustion Facility





The gooseneck, blowpipe, and 6in tuyere are Stelco stock. The water-cooled furnace (48in diameter, 10 ft long) is lined with 90 percent alumina refractory brick.

To sample the slurry flames inside the furnace we used 2in water-cooled stainless probes, spaced at 1 ft intervals along the furnace axis. Tungsten/rhenium (W/W 6 percent Re) thermocouples, one located opposite each gas sampling probe, recorded furnace temperatures.

During operation, part of the hot gases exhausted to atmosphere. A portion of the exhaust returned to the hot side of the heat exchanger. A 4 psi blower delivered the combustion air to the cold side of the heat exchanger. After passing through the heat exchanger, the combustion air entered a natural gas booster heater, which raised the hot blast temperature to the desired 1800°F. Since the booster consumed oxygen and added inert combustion gases (CO_2 and H_2O) to the hot blast, oxygen was added to the hot blast to raise it to 21 percent. Oxygen enrichment above 21 percent was not done.

Test Procedure

Tables I AIII, II AIII, and III AIII list each of the slurries tested during the combustion trials.

Table I AIII: No 6C Oil Slurries

Coal Size (mesh)	Coal Concentration (Wt %)	Injection Rate (lb/min)	Test Number
0	0 0	4.5 6	1, 2 3, 4
-100	25	4.5	21

Table II AIII: No 6P Oil Slurries

Coal Size (mesh)	Coal Concentration (Wt %)	Injection Rate (lb/min)	Test Number
0	0	4.5	5, 7
	0	6	6, 8
-100	25	4.5	9, 33
	25	6	10, 34
	50	4.5	11, 35
	50	6	12, 36
	65	6	116, 117
-35	25	4.5	13, 115
	25	6	14, 114
	50	4.5	15, 113
	50	6	16, 112
	65	6	110, 111
-10	25	4.5	101, 103
	25	6	100, 102
	50	4.5	105, 107
	50	6	104, 106

Table III AIII: Tar Slurries

Coal Size (mesh)	Coal Concentration (Wt %)	Injection Rate (lb/min)	Test Number
0	0	4.5	119, 121
	0	6	118, 120
-100	25	4.5	123, 125
	25	6	122, 124
	50	4.5	127, 129
	50	6	126, 128
-35	25	4.5	131, 133
	25	6	130, 132
	50	4.5	135, 137
	50	6	134, 136
-10	25	4.5	139, 141
	25	6	138, 140
	50	4.5	143
	50	6	142

Originally, we had planned to test more No 6C oil-based slurries, and not to repeat slurries of minus 35 mesh coal. After completing the No 6C oil tests (Table I AIII) we analyzed the results and decided that all tests (i.e., the minus 35 mesh coal) should be done twice. To compensate for the increased number of tests, we decided to eliminate one carrier fluid. We were interested in the effect of slurry viscosity, so we retained the No 6P oil and Tar tests (the viscosities of these two fluids differed the most). Also, we use No 6P oil at the blast furnace.

Load cells provided the weighing mechanism for batching the slurries. Each slurry was made up directly in the slurry tank by adding the appropriate weights of liquid carrier and coal.

The slurry was continuously agitated in the tank. Slurry temperature was approximately 200°F in the tank and approximately 180°F at the lance.

The load cell system monitored the slurry feed rate. Constant adjustment of the variable speed pump drive was required to maintain a steady injection rate.

Particulate sampling, in the center of the flame 5 ft downstream of the tuyere, was done at the beginning of each test. During the particulate sampling, the radial gas samples were taken 4 ft downstream of the

tuyere. The radial samples were taken in order 10, 5, and 2.5in from the furnace centerline, so as not to interfere with the particulate sampling. Once the particulate sampling was complete, we took the remaining axial (centerline) gas samples.

Steady-state operation at each probe location was ascertained by continuous gas analysis (CO, CO_2 and O_2). Once steady-state was achieved, we activated the data acquisition system a minimum of 3 times at intervals of approximately 30 seconds. We subsequently averaged these readings during analysis. Each time a furnace gas sample was obtained, the data acquisition system automatically recorded the hot blast temperature, CO_2 and O_2 content and the furnace temperatures.

Each test took approximately 3 hours (about 200 hours altogether). One full tank of slurry was usually sufficient for two to four tests, depending on the delays caused by flow rate fluctuations. If sufficient slurry remained in the tank, then the next test began as soon as the new slurry injection rate was achieved.

Evaluation of Slurry Combustion

i) Visual

We evaluated each slurry by watching the plume at the lance tip (lance plume) and by watching the furnace exhaust. At the blast furnace, only observation of the lance plume is possible. For many slurries, we photographed the lance plume and furnace exhaust.

ii) Particulates

We used one of the gas sampling probes to sample particulates at the flame centerline 5 ft from the tuyere nose. We used a Scott Isokinetic Stack sampler, Model No 100. We sampled at the maximum rate possible, but this was less than the isokinetic rate. Sampling time was 20 minutes.

The particulate gas sampling data is presented in Tables IV AIII and V AIII.

Table IV AIII: Furnace Gas Moisture and Particulate Load for No 6P Oil-Based Slurries

Coal Size (mesh)	Coal Concentration (Wt %)	Injection Rate (lb/min)	Test No	Gas Analyses	
				Moisture (grains/ft³ dry gas)	Particulate (10^{-4} grains/ft³ dry gas)
0	0	4.5	5	28.3	4021
			7	42.1	2348
		6	6	40.4	1903
			8	49.3	450
-100	25	4.5	9	29.1	140
			33	38.4	470
		6	10	42.9	370
			34	57.3	504
	50	4.5	11	37.5	111
			35	38.4	1110
		6	12	42.0	382
			36	62.4	287
	65	6	116	38.9	367
			117	42.6	287
-35	25	4.5	13	34.9	1061
			115	33.4	1435
		6	14	38.1	208
			114	46.8	361
	50	4.5	15	33.0	372
			113	34.1	745
		6	16	38.8	893
			112	34.0	1132
	65	6	110	35.4	606
			111	40.4	315
-10	25	4.5	101	37.6	594
			103	37.2	475
		6	100	39.6	99
			102	46.3	83
	50	4.5	105	37.4	265
			107	31.5	506
		6	104	29.4	299
			106	45.0	348

Table V AIII: Furnace Gas Moisture and Particulate Load for Tar-Based Slurries

Coal Size (mesh)	Coal Concentration (Wt %)	Injection Rate (lb/min)	Test No	Gas Analyses	
				Moisture (grains/ft³ dry gas)	Particulate (10^{-4} grains/ft³ dry gas)
0	0	4.5	119 121	27.4 27.4	321 896
		6	119 120	30.8 27.3	293 768
-100	25	4.5	123 125	29.0 27.1	46 748
		6	122 124	33.8 32.3	1050 154
	50	4.5	127 129	23.8 23.0	204 1070
		6	126 128	32.8 31.2	854 1488
-35	25	4.5	131 133	26.0 26.1	287 142
		7	130 132	29.1 31.6	937 170
	50	4.5	135 137	23.4 26.2	384 299
		6	134 136	28.8 26.7	996 598
-10	25	4.5	139 141	24.7 27.8	170 151
		6	138 140	29.7 29.5	278 204
	50	6	142	27.3	169

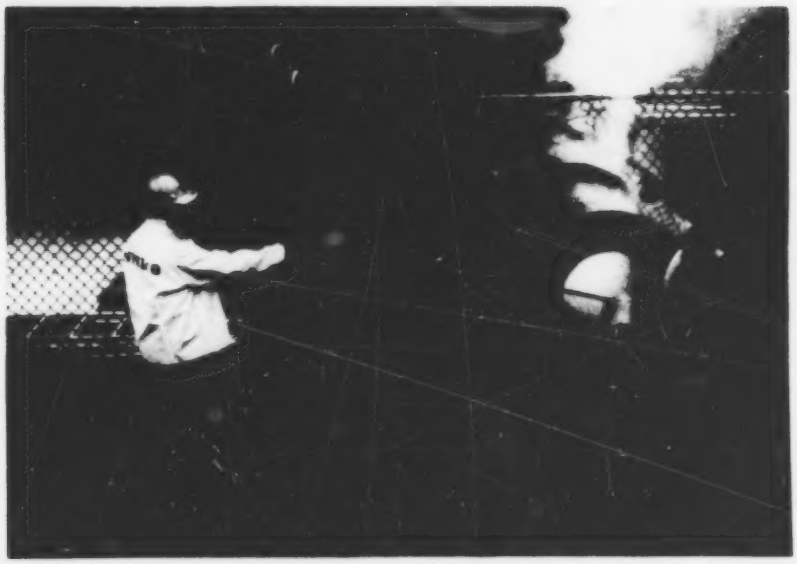
The data is summarized in Table VI AIII. Unfortunately, the data are inconclusive and were not used to evaluate slurry combustion. The particulates sampled with the Scott sampler were not analyzed for volatile matter content.

Table VI AIII: Furnace Gas Particulate Load

Slurry Coal Concentration and Size	Injection Rate (lb/min)	Avg Gas Particulate Load (10^{-4} grains/ft^3 dry gas)	
		No 6P Oil	Tar
25 and 50 wt % of -100 mesh 25 and 50 wt % of -35 mesh 25 wt % of -10 mesh	4.5 and 6	542	507
25 and 50 wt % of -100 mesh 25 and 50 wt % of -35 mesh 25 wt % of -10 mesh	4.5	652	351
25 and 50 wt % of -100 mesh 25 and 50 wt % of -35 mesh 25 wt % of -10 mesh	6	432	663
25 and 50 wt % of -100 mesh 25 and 50 wt % of -35 mesh 25 wt % of -10 mesh	4.5 and 6	422 776 313	702 464 201

We also sampled the particulates exhausting from the furnace (figure 2 AIII).

Figure 2 AIII: Sampling Exhaust Particulates



We did not sample each slurry flame nor did we follow a set sampling procedure. We sampled long enough to obtain sufficient particulates for size and chemical analyses (a minimum of 5 grams). We used the volatile matter of the particulates (percent dry-ash-free basis) as a measure of the extent of combustion of the coal.

iii) Furnace Temperatures

Each time we took a gas sample, the data acquisition system automatically recorded furnace temperatures. During the first series of combustion tests (tests numbered less than 100) the shielded tungsten/rhenium (W/W 6 percent Re) thermocouples were inserted 2in inside the furnace (2in past the refractory). Unfortunately several thermocouples failed, so for the second series of tests (100 series) we changed the thermocouple depth to 0.25in. This resulted in a recorded temperature reduction of approximately 800°F.

The average temperatures for the last 40 minutes of each test are listed in Tables VII AIII, VIII AIII, and IX AIII.

Table VII AIII: Furnace Temperatures for No 6C Oil-Based Slurries

Coal Size (mesh)	Coal Concentration (Wt %)	Injection Rate (lb/min)	Test No	Temperature (°F)		
				Thermocouple Location* (ft from Tuyere Nose)		
				3	5	7
0	0	4.5	1	1553	1688	-
			2	1575	1638	-
		6	3	1857	1935	-
			4	1797	1857	-
-100	25	4.5	21	1560	1658	-

* thermocouples inserted 2in past refractory wall

Table VIII AIII: Furnace Temperatures for No 6P Oil-Based Slurries

Coal Size (mesh)	Coal Concentration (Wt %)	Injection Rate (lb/min)	Test No	Temperature (°F)		
				Thermocouple Location* (ft from Tuyere Nose)		
				3	5	7
0	0	4.5	5 7	1964 2076	1933 1972	1996 2160
		6	6 8	2266 2363	2162 2219	2372 2435
-100	25	4.5	9 33	1923 1985	1998 1913	1987 2031
		6	10 34	2322 2275	2213 2186	2367 2327
	50	4.5	11 35	1865 1787	1880 1874	1949 1912
		6	12 36	2208 -	2056 2062	2248 2238
	65	6	116 117	1013 1021	1178 1258	1342 1479
-35	25	4.5	13 115	- 936	1962 1047	1965 1222
		6	14 114	- 1062	2173 1305	2269 1469
	50	4.5	15 113	- 965	1840 1160	1849 1231
		6	16 112	- 923	2041 1059	2056 1262
	65	6	110 111	1040 1069	1225 1274	1410 1420
-10	25	4.5	101 103	921 914	1054 1106	1251 1356
		6	100 102	1012 1039	1199 1287	1524 1565
	50	4.5	105 107	979 974	1149 1151	1205 1213
		6	104 106	1000 1018	1193 1206	1267 1289

* for tests numbered less than 100, thermocouples inserted 2in past refractory wall. For tests numbered in 100's, thermocouples inserted 0.25in past refractory wall.

Table IX AIII: Furnace Temperatures for Tar-Based Slurries

Coal Size (mesh)	Coal Concentration (Wt %)	Injection Rate (lb/min)	Test No	Temperature (°F)		
				Thermocouple Location* (ft from Tuyere Nose)		
				3	5	7
3	0	4.5	119 121	1240 1143	1509 1464	1274 1262
		6	118 120	1129 1351	1379 1653	1308 1398
-100	25	4.5	123 125	966 936	1320 1292	1264 1248
		6	122 124	1040 1065	1461 1463	1370 1394
	50	4.5	128 129	1023 1067	1293 1348	1208 1274
		6	126 128	918 1030	1246 1388	1292 1345
-35	25	4.5	131 133	929 923	1279 1206	1180 1162
		6	130 132	1024 1006	1395 1350	1324 1311
	50	4.5	135 137	922 922	1205 1168	1164 1160
		6	134 136	1026 926	1349 1214	1273 1236
-10	25	4.5	139 141	862 868	1101 1096	1100 1070
		6	138 140	961 950	1247 1200	1265 1263
	50	4.5	143	790	922	927
		6	142	839	1025	998

* thermocouples inserted 0.25in past refractory wall

We did not use the thermocouple data to evaluate the slurries; however, the data clearly show the effect of injection rate (the higher the injection rate, the higher the temperature, as would be expected).

iv) Furnace Gas
Analysis

We took furnace gas samples axially (along the furnace centerline) at 1 ft intervals from the tuyere nose and radially, 4 ft from the tuyere nose, at 10, 5, and 2.5in from the centerline. The oxygen, carbon monoxide, and carbon dioxide (O_2, CO, and CO_2) contents of the gases were measured. (The furnace gas composition for each slurry is given in a later section.)

To evaluate the slurries we used only the CO_2 values measured at 3, 4, and 5 ft from the tuyere. These distances correspond to the approximate depth of the blast furnace raceway (Appendix II). Unfortunately, constant plugging of the first two probes (1 and 2 ft from the tuyere) meant insufficient and unreliable data for those two sampling positions.

• *CO_2 Ratio*

We used the fuel injection rate, the fuel chemistry, the hot blast volume, and the hot blast chemistry to compute a theoretical CO_2 furnace gas concentration. The fuel injection rate, hot blast volume, and hot blast chemistry varied continuously. The injection rate was monitored every 5 minutes, the blast volume every 30 minutes, and the blast chemistry continuously. For each test, we used the aim fuel injection rate (4.5 or 6 lb/min). We also used the average hot blast volume and average hot blast oxygen concentration (obtained from data supplied by ORF).

The measured furnace CO_2 concentrations were corrected to account for the hot blast CO_2 (a combustion product of the natural gas burned in the booster heater). The data acquisition system recorded the hot blast CO_2 each time a furnace gas sample was taken. Each furnace CO_2 value was corrected by subtracting its corresponding hot blast CO_2 value (approximately 2 percent).

For statistical analysis, we used the ratio of the measured or experimental CO_2 to the calculated or theoretical CO_2. These CO_2 ratios are provided in Tables X AIII to XVII AIII.

Table X AIII: CO_2 Ratios for No 6P Oil

Injection Rate (lb/min)	Probe No	CO_2 Ratios					
		Wheel No 1			Converted to Wheel No 2		
		Replicate No 1	Replicate No 2	Avg	Replicate No 1	Replicate No 2	Avg
4.5	3	1.12	1.12	1.12	0.90	0.90	0.90
	4	1.08	1.07	1.08	0.91	0.91	0.91
	5	0.94	1.00	0.97	0.79	0.84	0.81
6	3	1.03	0.97	1.00	0.82	0.78	0.80
	4	1.08	0.99	1.03	0.90	0.84	0.87
	5	0.97	1.02	1.00	0.81	0.85	0.83

Table XI AIII: CO_2 Ratios for Minus 100 Mesh Coal in No 6P Oil

Coal Concentration (Wt %)	Injection Rate (lb/min)	Probe No	CO_2 Ratios					
			Wheel No 1			Converted to Wheel No 2		
			Replicate No 1	Replicate No 2	Avg	Replicate No 1	Replicate No 2	Avg
25	4.5	3	1.21	1.04	1.13	0.97	0.83	0.90
		4	1.04	0.99	1.02	0.88	0.84	0.86
		5	0.98	0.59	0.79	0.82	0.49	0.82*
	6	3	1.03	1.15	1.09	0.82	0.92	0.87
		4	1.06	0.66	0.86	0.89	0.56	0.89*
		5	1.05	0.78	0.92	0.88	0.65	0.77
50	4.5	3	1.21	1.27	1.24	0.97	1.02	1.00
		4	1.15	1.17	1.16	0.97	0.99	0.98
		5	1.03	1.09	1.06	0.86	0.91	0.89
	6	3	1.00	1.19	1.10	0.80	0.95	0.88
		4	0.93	1.17	1.05	0.78	0.99	0.89
		5	0.97	1.12	1.05	0.81	0.94	0.88
65	6	3	-	-	-	0.77	0.83	0.80
		4	-	-	-	0.75	0.82	0.79
		5	-	-	-	0.77	0.76	0.77

* Replicate No 2 not used in average

Table XII AIII: CO_2 Ratios for Minus 35 Mesh Coal in No 6P Oil

Coal Concentration (Wt %)	Injection Rate (lb/min)	Probe No	CO_2 Ratios			
			Wheel No 1	Wheel No 2		
			Replicate No 1	Converted Replicate No 1	Replicate No 2	Avg
25	4.5	3	1.24	0.99	1.02	1.01
		4	1.11	0.94	0.92	0.93
		5	1.11	0.93	0.96	0.96
	6	3	1.22	0.97	0.93	0.95
		4	1.09	0.92	0.90	0.91
		5	1.08	0.90	0.91	0.91
50	4.5	3	1.04	0.83	0.82	0.83
		4	0.95	0.80	0.83	0.82
		5	0.92	0.77	0.85	0.81
	6	3	0.93	0.74	0.77	0.76
		4	0.88	0.74	0.75	0.75
		5	1.00	0.84	0.72	0.78

			Wheel No 2		
			Replicate No 1	Replicate No 2	Avg
65	6	3	0.87	0.88	0.88
		4	0.85	0.91	0.88
		5	0.79	0.83	0.81

Table XIII AIII: CO_2 Ratios for Minus 10 Mesh Coal in No 6P Oil

Coal Concentration (Wt %)	Injection Rate (lb/min)	Probe No	CO_2 Ratio (Wheel No 2)		
			Replicate No 1	Replicate No 2	Avg
25	4.5	3	0.77	0.87	0.82
		4	0.73	0.84	0.79
		5	0.81	0.81	0.81
	6	3	0.75	0.84	0.80
		4	0.70	0.89	0.80
		5	0.78	1.05	0.92
50	4.5	3	0.79	0.84	0.82
		4	0.80	0.81	0.81
		5	0.78	0.78	0.78
	6	3	0.62	0.69	0.66
		4	0.66	0.71	0.69
		5	0.67	0.73	0.70

Table XIV AIII: CO_2 Ratios for Tar

Injection Rate (lb/min)	Probe No	CO_2 Ratio (Wheel No 2)		
		Replicate No 1	Replicate No 2	Avg
4.5	3	0.94	0.97	0.96
	4	0.96	0.93	0.95
	5	0.97	0.96	0.97
6	3	1.07	0.87	0.97
	4	0.96	0.88	0.92
	5	0.89	0.92	0.91

Table XV AIII: CO_2 Ratios for Minus 100 Mesh Coal in Tar

Coal Concentration (Wt %)	Injection Rate (lb/min)	Probe No	CO_2 Ratio (Wheel No 2)		
			Replicate No 1	Replicate No 2	Avg
25	4.5	3	1.25	1.08	1.17
		4	0.99	1.03	1.01
		5	0.94	0.93	0.94
	6	3	0.99	0.45*	0.99
		4	0.98	0.46*	0.98
		5	0.87	0.58*	0.87
50**	4.5	3	1.35	1.52	1.44
		4	0.85	0.91	0.88
		5	0.81	0.93	0.87
	6	3	1.03	1.23	1.13
		4	1.07	0.96	1.02
		5	1.14	0.87	1.01

* Replicate No 2 not used in average
** All tests of 50 wt % of minus 100 mesh coal in tar were omitted

Table XVI AIII: CO_2 Ratios for Minus 35 Mesh Coal in Tar

Coal Concentration (Wt %)	Injection Rate (lb/min)	Probe No	CO_2 Ratio (Wheel No 2)		
			Replicate No 1	Replicate No 2	Avg
25	4.5	3	0.97	0.98	0.98
		4	0.88	0.93	0.91
		5	0.95	0.92	0.94
	6	3	0.87	0.92	0.90
		4	0.81	0.85	0.83
		5	0.88	0.89	0.89
50	4.5	3	0.81	1.18	1.00
		4	0.80	0.98	0.89
		5	0.91	0.92	0.92
	6	3	0.80	0.84	0.82
		4	0.82	0.87	0.85
		5	0.82	0.86	0.84

Table XVII AIII: CO_2 Ratios for Minus 10 Mesh Coal in Tar

Coal Concentration (Wt %)	Injection Rate (lb/min)	Probe No	CO_2 Ratio (Wheel No 2)		
			Replicate No 1	Replicate No 2	Avg
25	4.5	3	0.85	0.81	0.83
		4	0.94	0.93	0.94
		5	0.93	0.82	0.88
	6	3	0.82	0.83	0.83
		4	0.89	0.89	0.89
		5	0.87	0.87	0.87
50*	6	3	0.56	-	0.56
		4	0.72	-	0.72
		5	0.73	-	0.73

* Tests ended after Replicate No 1

This CO_2 ratio is an indication of the extent of combustion of the slurry, with unity indicating complete combustion. By using this CO_2 ratio, we assumed that the flame pattern was the same for each slurry (i.e., each slurry flame had the same centerline). We believe that this assumption was valid for all slurries except 50 wt percent of minus 100 mesh coal in tar (see discussion of coal concentration in report body).

- *Data Correction: Variable Operating Conditions*

Due to problems with the heat exchanger, we operated with two very different hot blast conditions. We designated these conditions Wheel No 1 and Wheel No 2 (Tables X AIII to XII AIII). ORF, who were responsible for maintaining stable and consistent operating conditions, were not aware of the change in conditions until after the testing was finished.

For the tests with minus 35 mesh coal in No 6P oil we did the first set of replicates (tests) under Wheel No 1 conditions and we did the second set under Wheel No 2 conditions (Table XII AIII, 25 and 50 wt percent coal). The CO_2 ratios for the first set of replicates were consistently greater than the corresponding CO_2 ratios for the Wheel No 2 replicates. Theoretically, the ratios would have been equal had the operating conditions been the same. The actual operating conditions are listed in Table XVIII AIII.

Table XVIII AIII: Excess Air and Blast Velocity Slurries of Minus 35 Mesh Coal in No 6P Oil

Coal Concentration (Wt %)	Fuel Rate (lb/min)	Excess Air (%)		Blast Velocity (ft/sec)	
		Wheel Number			
		1	2	1	2
25	4.5	144	122	676	612
	6	80	64	669	607
50	4.5	160	125	670	581
	6	100	74	673	592

The results for the minus 35 mesh coal in No 6P oil suggested that, possibly, all replicates done with Wheel No 1 (pure No 6P oil and minus 100 mesh coal in No 6P oil, Tables X AIII and XI AIII, respectively) would have greater CO_2 ratios than had they been done with Wheel No 2. In order to compare replicates done with different wheel conditions, we developed conversion factors and used them to reduce the CO_2 ratios of Wheel No 1 replicates. Since the minus 35 mesh coal in No 6P oil replicates were the only measure we had of the effect of wheel conditions, we used those results to develop the conversion factors, as follows:

Probe No 3:

$$\frac{\text{Repl No 2, Wheel No 2 } CO_2 \text{ Ratios}}{\text{Repl No 1, Wheel No 1 } CO_2 \text{ Ratios}} = \frac{1.02 + 0.93 + 0.82 + 0.77}{1.24 + 1.22 + 1.04 + 0.93} = 0.80$$

Probe No 4:

$$\frac{\text{Repl No 2, Wheel No 2 } CO_2 \text{ Ratios}}{\text{Repl No 1, Wheel No 1 } CO_2 \text{ Ratios}} = \frac{0.92 + 0.90 + 0.83 + 0.75}{1.11 + 1.09 + 0.95 + 0.88} = 0.84$$

Probe No 5:

$$\frac{\text{Repl No 2, Wheel No 2 } CO_2 \text{ Ratios}}{\text{Repl No 1, Wheel No 1 } CO_2 \text{ Ratios}} = \frac{0.96 + 0.91 + 0.85 + 0.72}{1.11 + 1.08 + 0.92 + 1.00} = 0.84$$

For example, for pure No 6P oil, at an injection rate of 4.5 lb/min and done with Wheel No 1 conditions, we calculated CO_2 ratios of 0.94 and 1.00 for the two replicates sampled at probe position No 5. Multiplying by the probe No 5 conversion factor, 0.84, yields converted CO_2 ratios of 0.79 and 0.84, respectively (Table X AIII). Thus, when comparing CO_2 ratios for pure No 6P oil to, for instance, minus 10 mesh coal in No 6P oil, the converted CO_2 ratios for the pure No 6P oil were used.

- *Statistical Analysis*

We used paired "t" tests to statistically evaluate the CO_2 ratios. The following study of the effect of fuel type (No 6P oil versus tar) illustrates the statistical evaluation.

The two wheel conditions greatly confounded the comparison of the two fuel types. Table XIX AIII shows that two opposite conclusions can be drawn when comparing pure No 6P oil to pure tar.

Table XIX AIII: Paired "t" Tests (Pure No 6P Oil versus Pure Tar)

CO_2 Ratios Paired	Conclusion
No 6P Oil (Wheel No 1)* versus Tar (Wheel No 2)**	No 6P Oil is better than Tar (98% confidence level)
No 6P Oil (Converted Wheel No 1)* versus Tar (Wheel No 2)	Tar is better than No 6P Oil (99% confidence level)

* data in Table X AIII
** data in Table XIV AIII

Visually, No 6P oil was significantly better than tar. These conflicting results suggest that the conversion factors derived from the minus 35 mesh slurries might not be applicable to the other Wheel No 1 tests (pure No 6P oil and minus 100 mesh coal in No 6P oil).

In the report body, it states that there is no difference between No 6P oil and tar at the 95 percent confidence level, but that at the 90 percent confidence level, tar is better than No 6P oil. This conclusion is based on slurries of the two fluids. Table XX AIII shows three slurry groupings that can be paired to test the significance of the two fluids.

All of the tar CO_2 ratios (Groups A, B, and C) of Table XX AIII were done with Wheel No 2. The No 6P oil CO_2 ratios of Group A were done with Wheel No 2. The additional No 6P oil CO_2 ratios of Group B were done with Wheel No 1 (subsequently converted) and Wheel No 2. All the additional CO_2 ratios of Group C were done with Wheel No 1, but have been converted.

Table XX AIII: CO_2 Ratios Used for Paired "t" Tests (No 6P Oil versus Tar)

Coal Size (mesh)	Coal Concentration (Wt %)	CO_2 Ratios		
		No 6P Oil	versus Tar	
-10	25	0.82	0.83	A, B, C
		0.79	0.94	
		0.81	0.88	
		0.80	0.83	
		0.80	0.89	
		0.92	0.83	
	50	0.66	0.56	A
		0.69	0.72	
		0.70	0.73	
-35	25	1.01	0.98	B, C
		0.93	0.91	
		0.95	0.94	
		0.95	0.90	
		0.91	0.83	
		0.91	0.89	
	50	0.83	1.00	C
		0.82	0.89	
		0.77	0.92	
		0.76	0.82	
		0.75	0.85	
		0.78	0.84	
0	0	0.90	0.96	
		0.91	0.95	
		0.81	0.97	
		0.80	0.97	
		0.87	0.92	
		0.83	0.91	
-100	25	0.90	1.17	
		0.96	1.01	
		0.82	0.94	
		0.87	0.99	
		0.89	0.98	
		0.77	0.87	

Table XXI AIII gives the results of paired "t" tests of the three groups of Table XX AIII.

Table XXI AIII: Paired "t" Tests for the Data of Table XI

Data Group	Confidence Level* (%)
A	61
B	90
C	99

* for each group, tar was better than No 6P oil

As the data set increases, the confidence level increases. The confidence level also increases as the amount of converted Wheel No 1 data increases. For Group B, the data set essentially includes only Wheel No 2 data, since the converted Wheel No 1 CO_2 ratios are similar to the Wheel No 2 CO_2 ratios (see Table XII AIII). We used Group B to draw major conclusions regarding No 6P oil and tar.

Flame Composition

The following figures (figures 3 AIII to 65 AIII) present the measured CO, CO_2 and O_2 flame compositions of each slurry. The radial samples were taken 4 ft downstream of the tuyere nose.

Figure 3 AIII: No 6C Oil (4.5 lb/min Injection Rate)

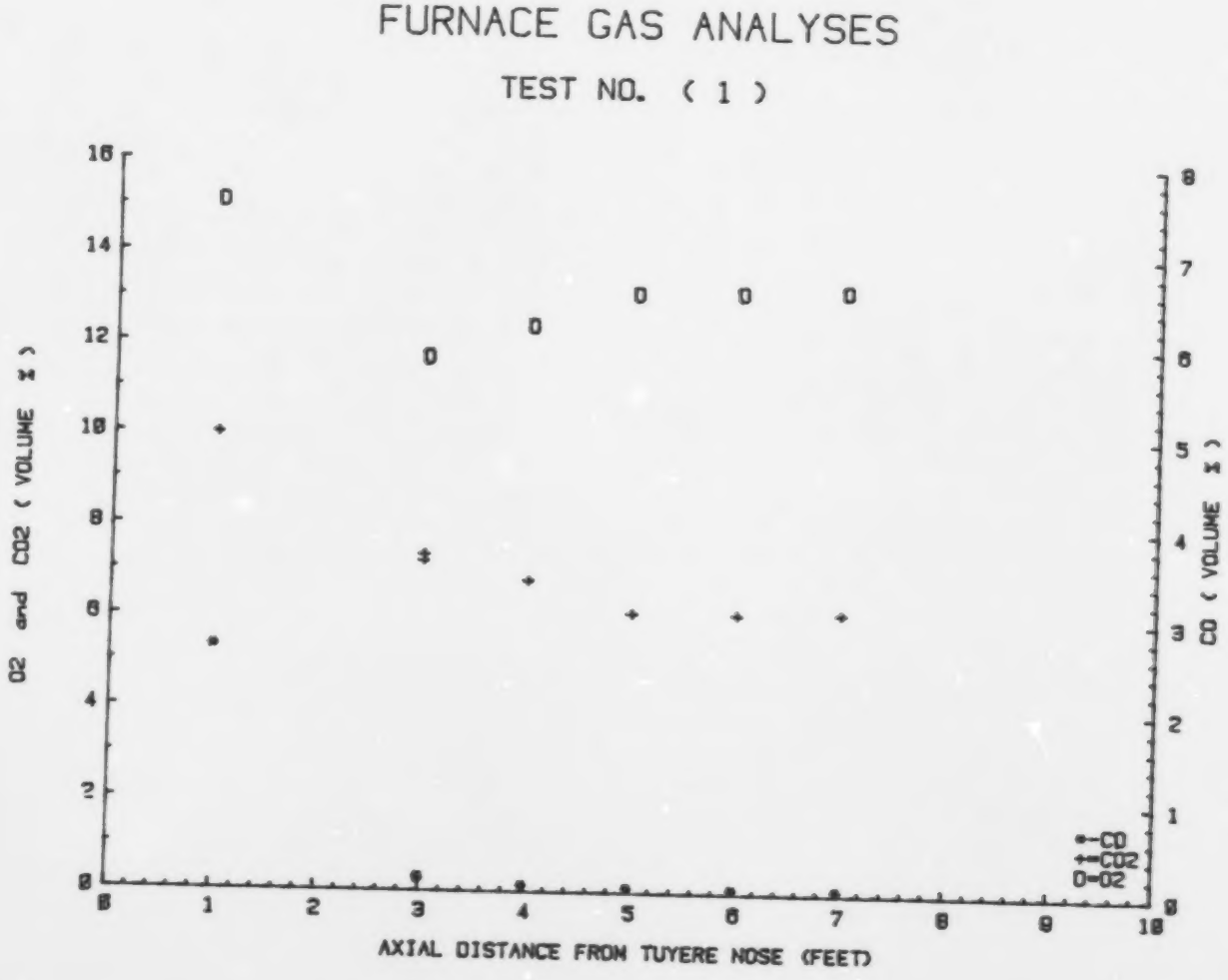


Figure 4 AIII: No 6C Oil (4.5 lb/min Injection Rate)

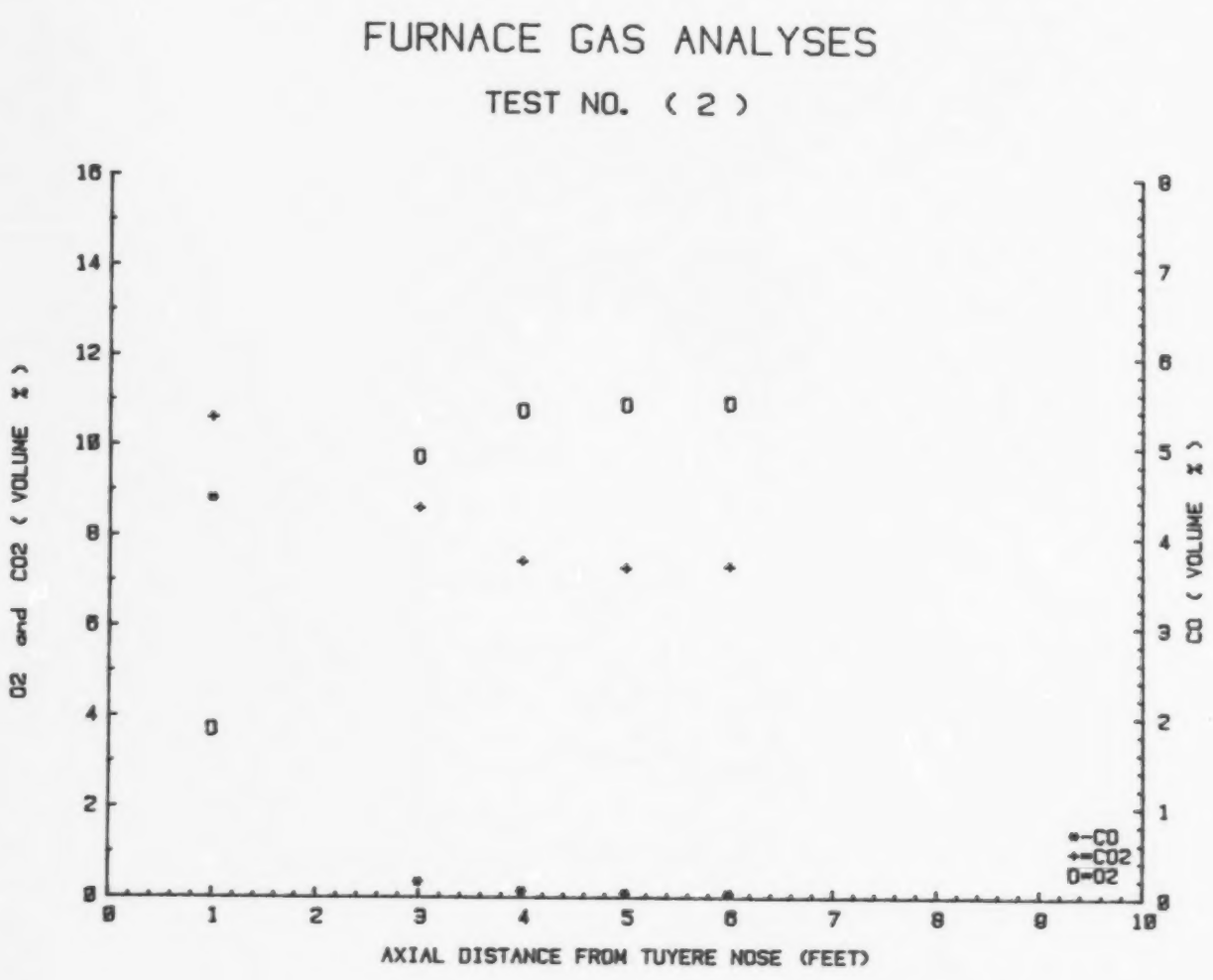


Figure 5 AIII: No 6C Oil (6 lb/min Injection Rate)

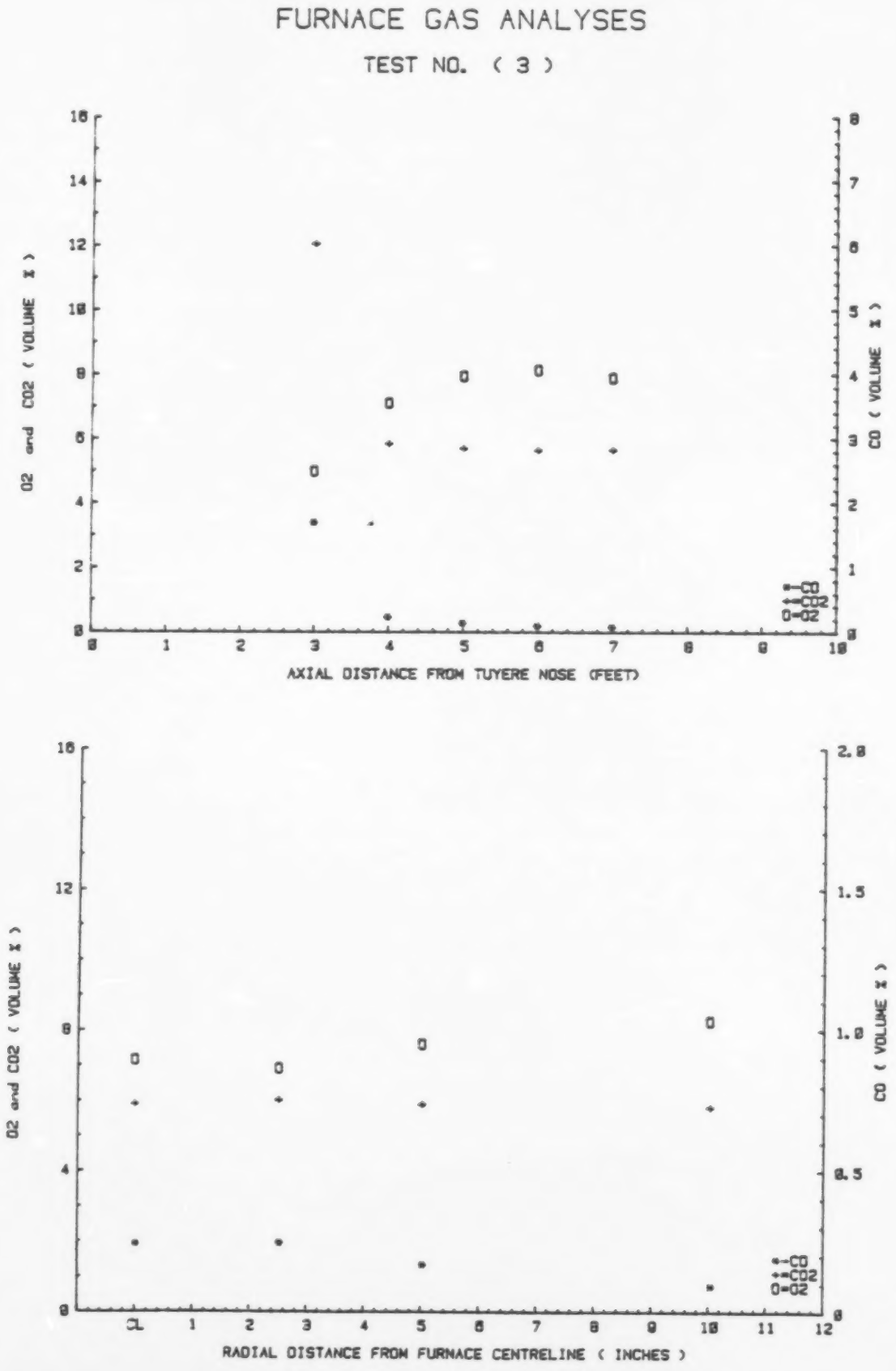

FURNACE GAS ANALYSES
TEST NO. (3)
O2 and CO2 (VOLUME %)
CO (VOLUME %)
AXIAL DISTANCE FROM TUYERE NOSE (FEET)
O-CO
+-CO2
O-O2
RADIAL DISTANCE FROM FURNACE CENTRELINE (INCHES)

Figure 6 AIII: No 6C Oil (6 lb/min Injection Rate)

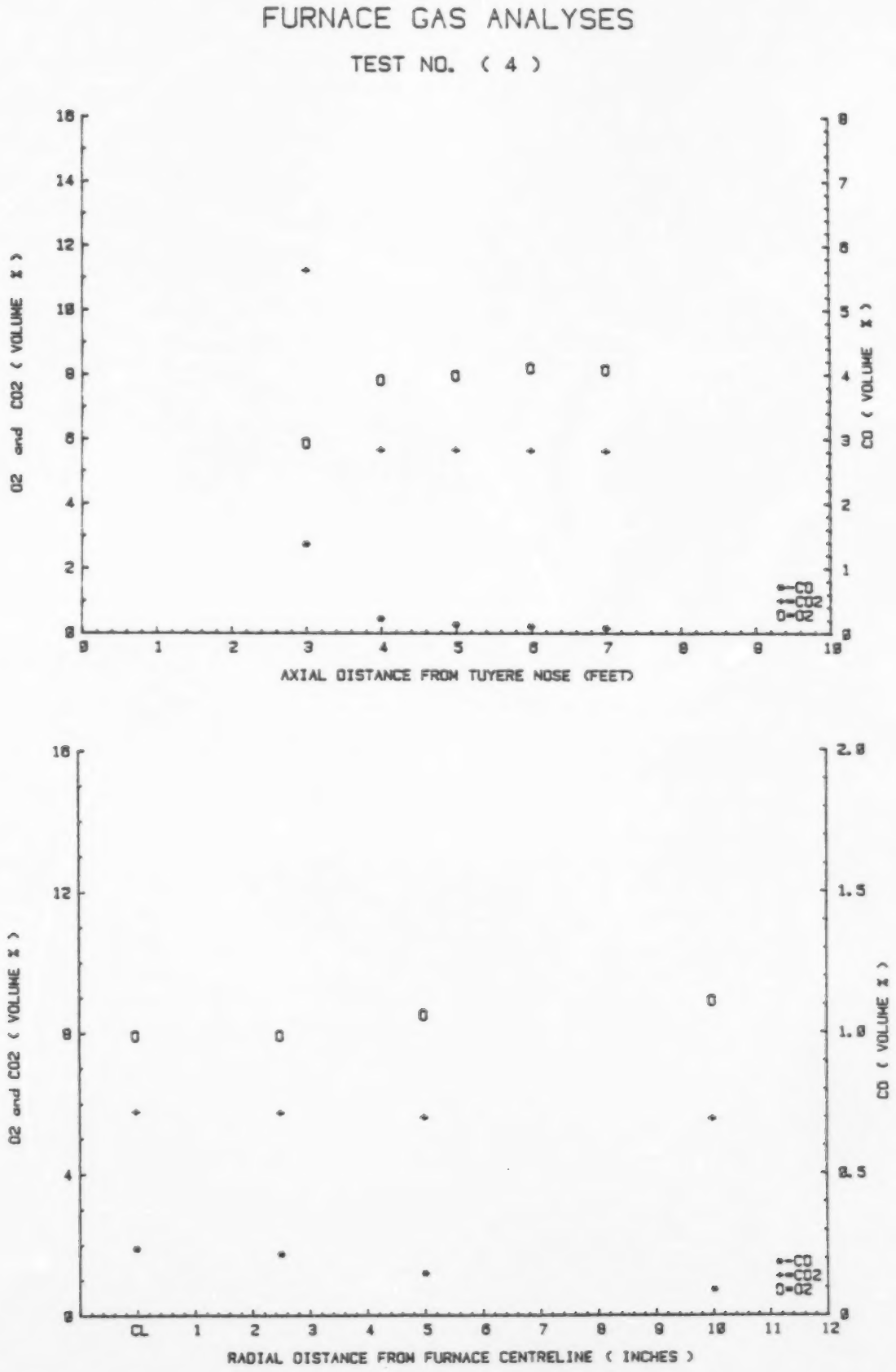


Figure 7 AIII: 25 Wt % Coal (minus 100 mesh) in No 6P Oil
(4.5 lb/min Injection Rate)

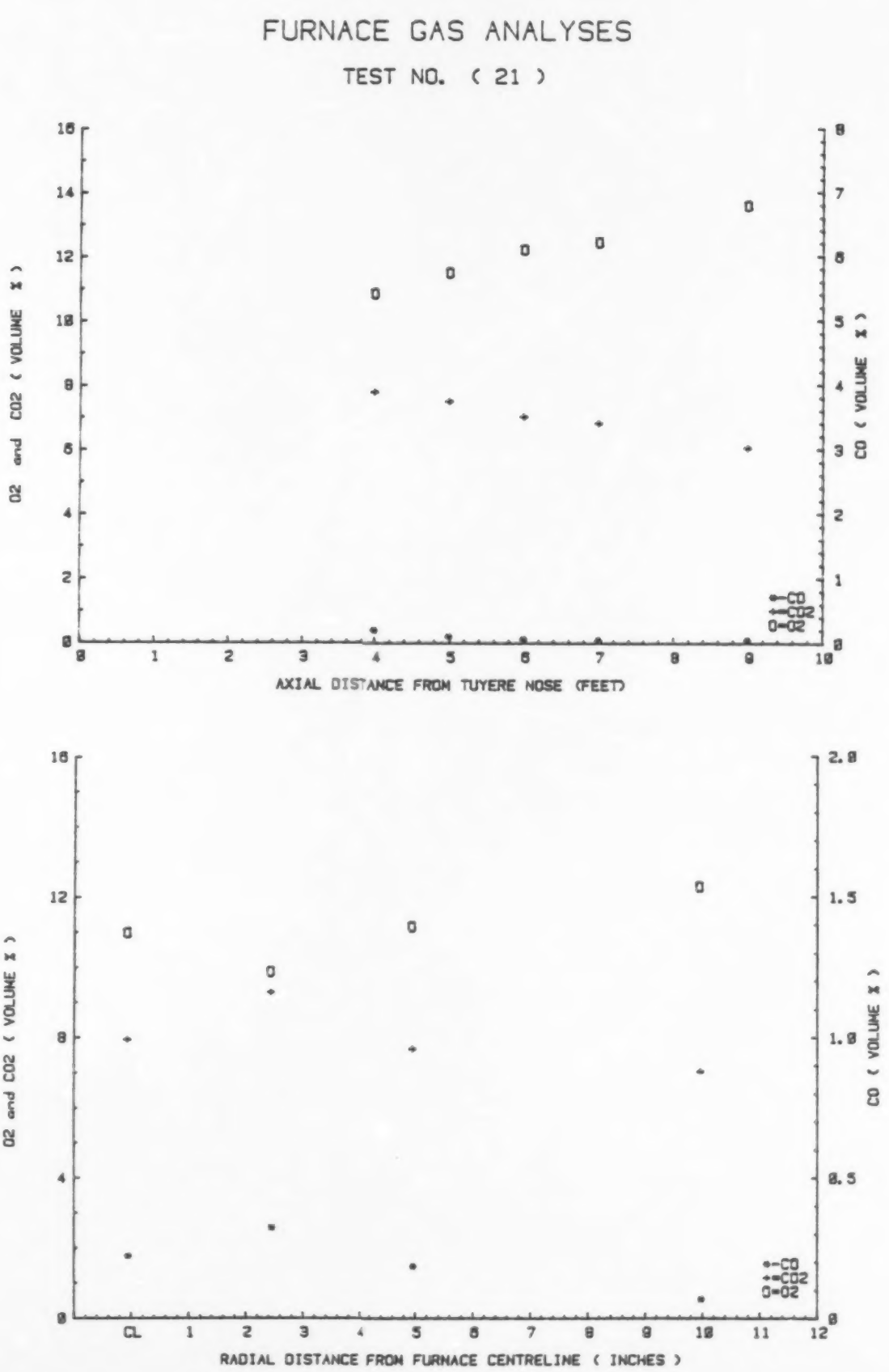


Figure 8 AIII: No 6P Oil (4.5 lb/min Injection Rate)

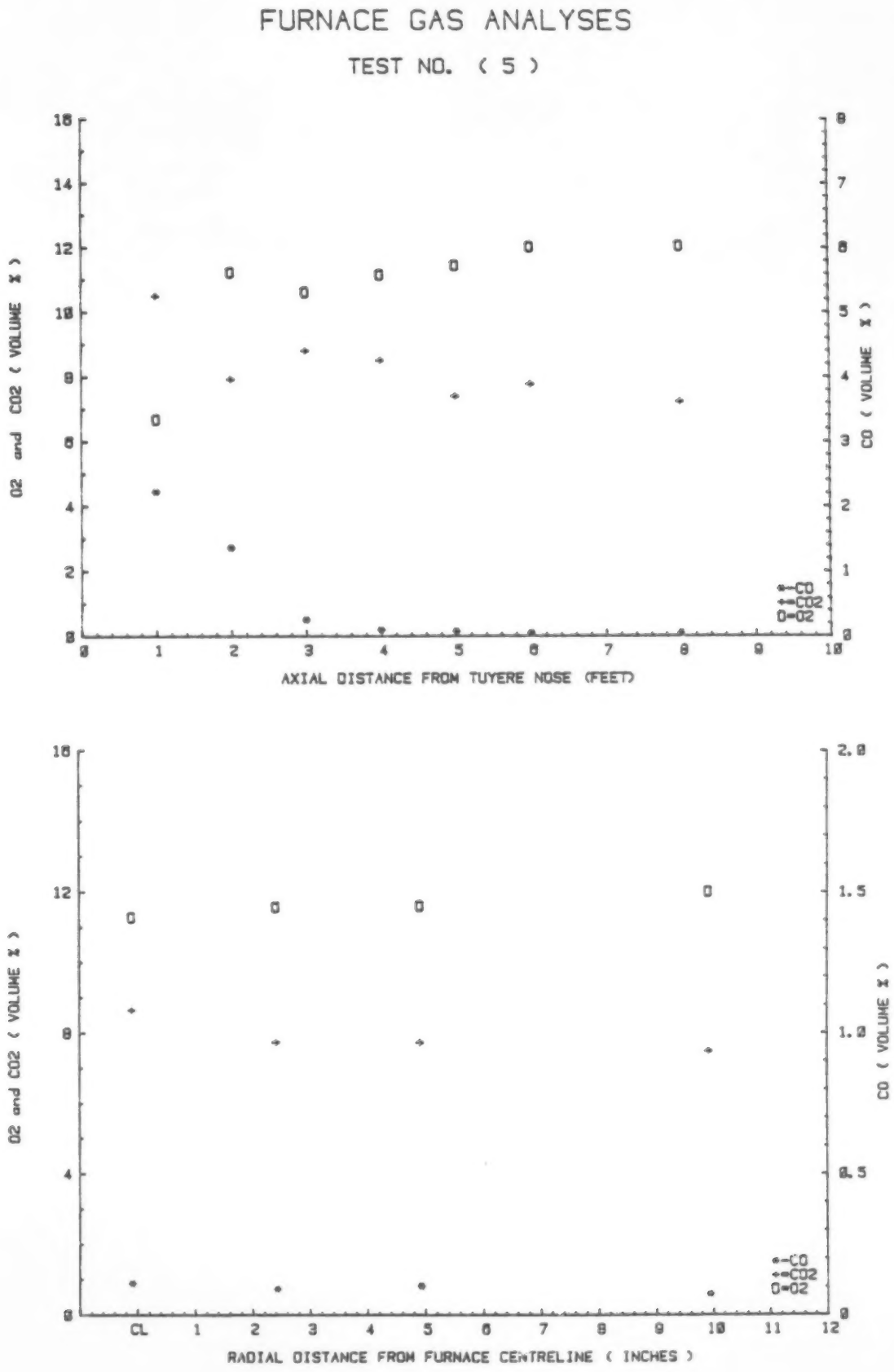


Figure 9 AIII: No 6P Oil (4.5 lb/min Injection Rate)

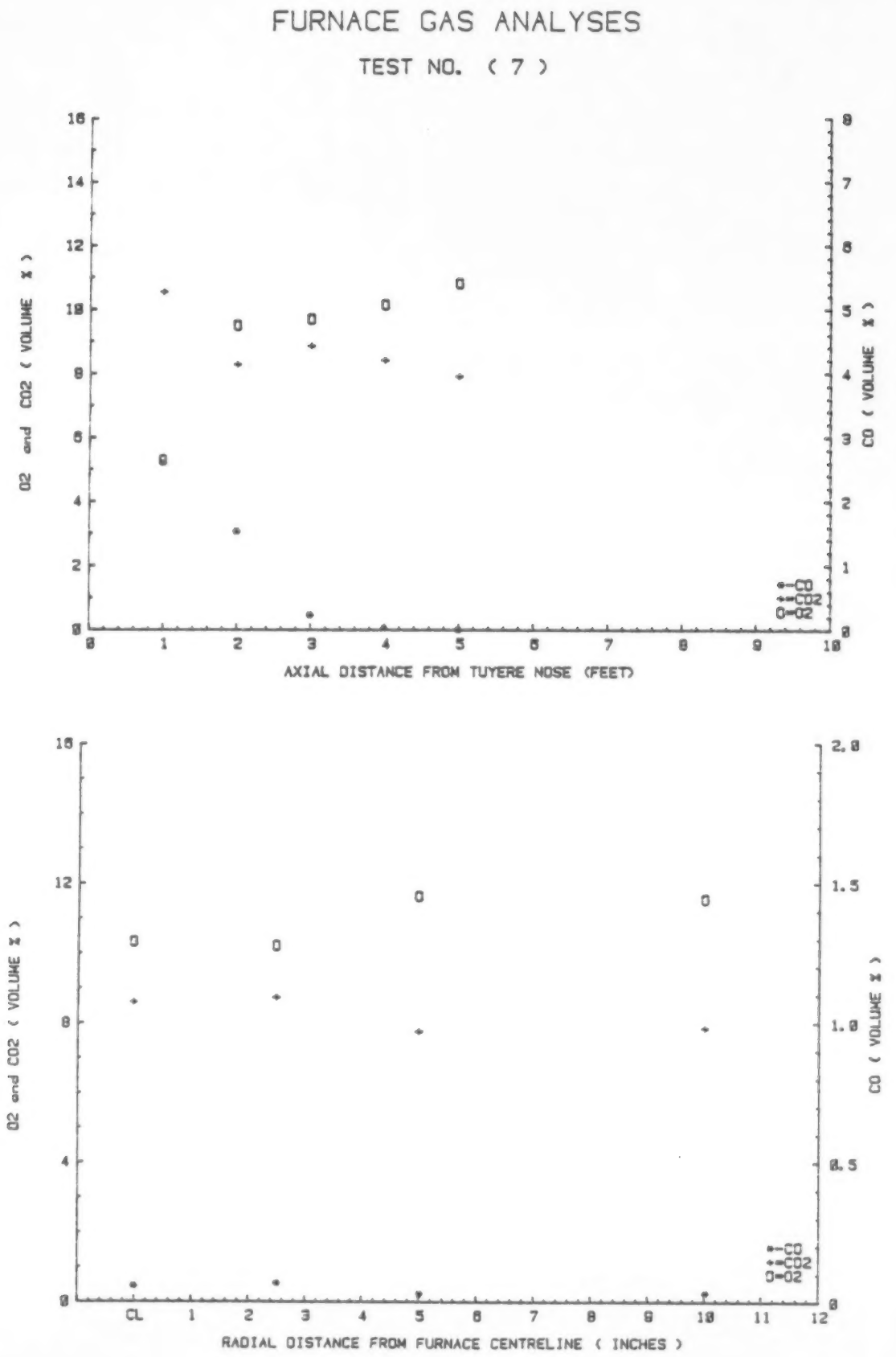

FURNACE GAS ANALYSES
TEST NO. (7)
O2 and CO2 (VOLUME %)
CO (VOLUME %)
AXIAL DISTANCE FROM TUYERE NOSE (FEET)
O=CO
+=CO2
O=O2
RADIAL DISTANCE FROM FURNACE CENTRELINE (INCHES)

Figure 10 AIII: No 6P Oil (6 lb/min Injection Rate)

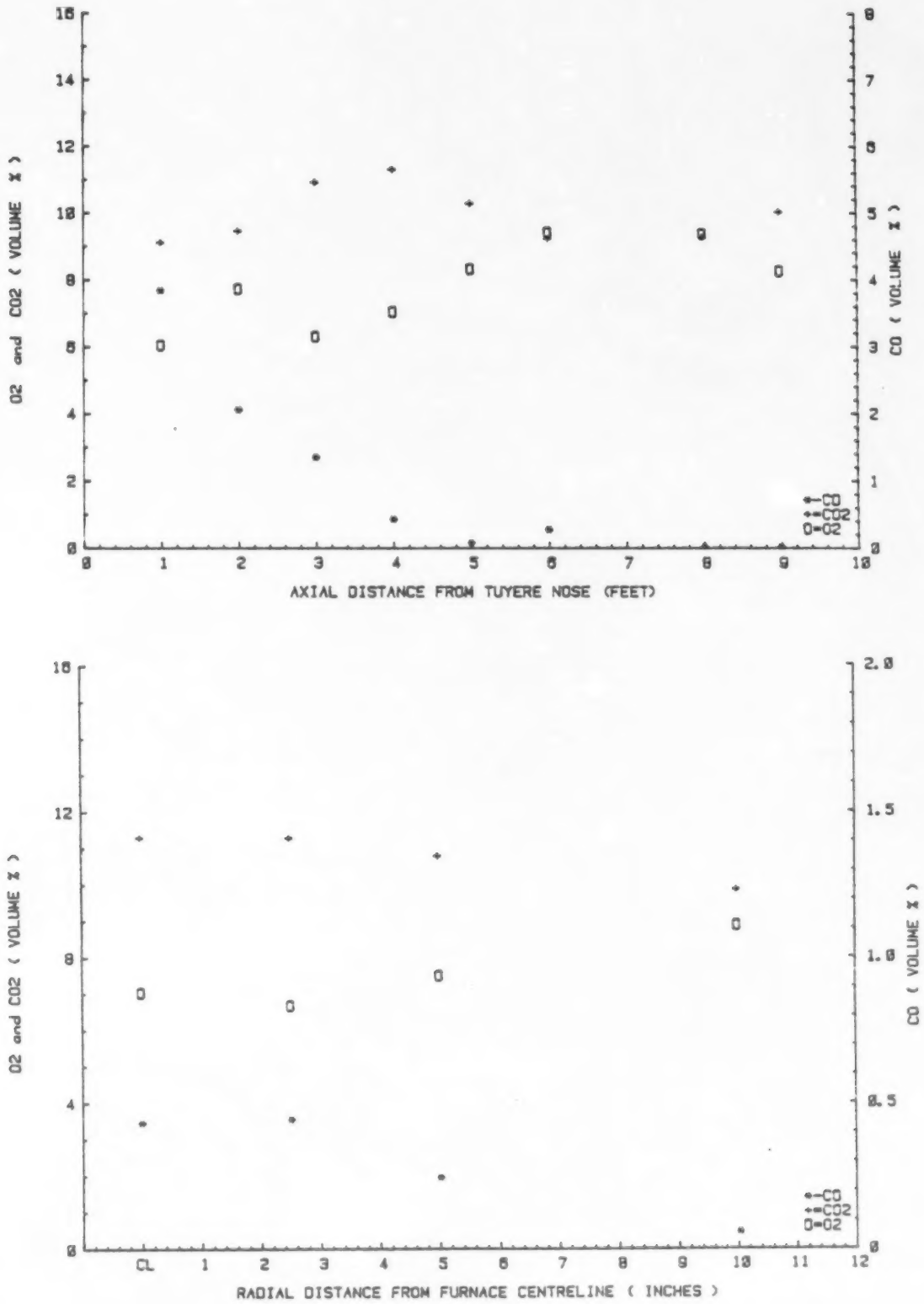


Figure 11 AIII: No 6 P Oil (6 lb/min Injection Rate)

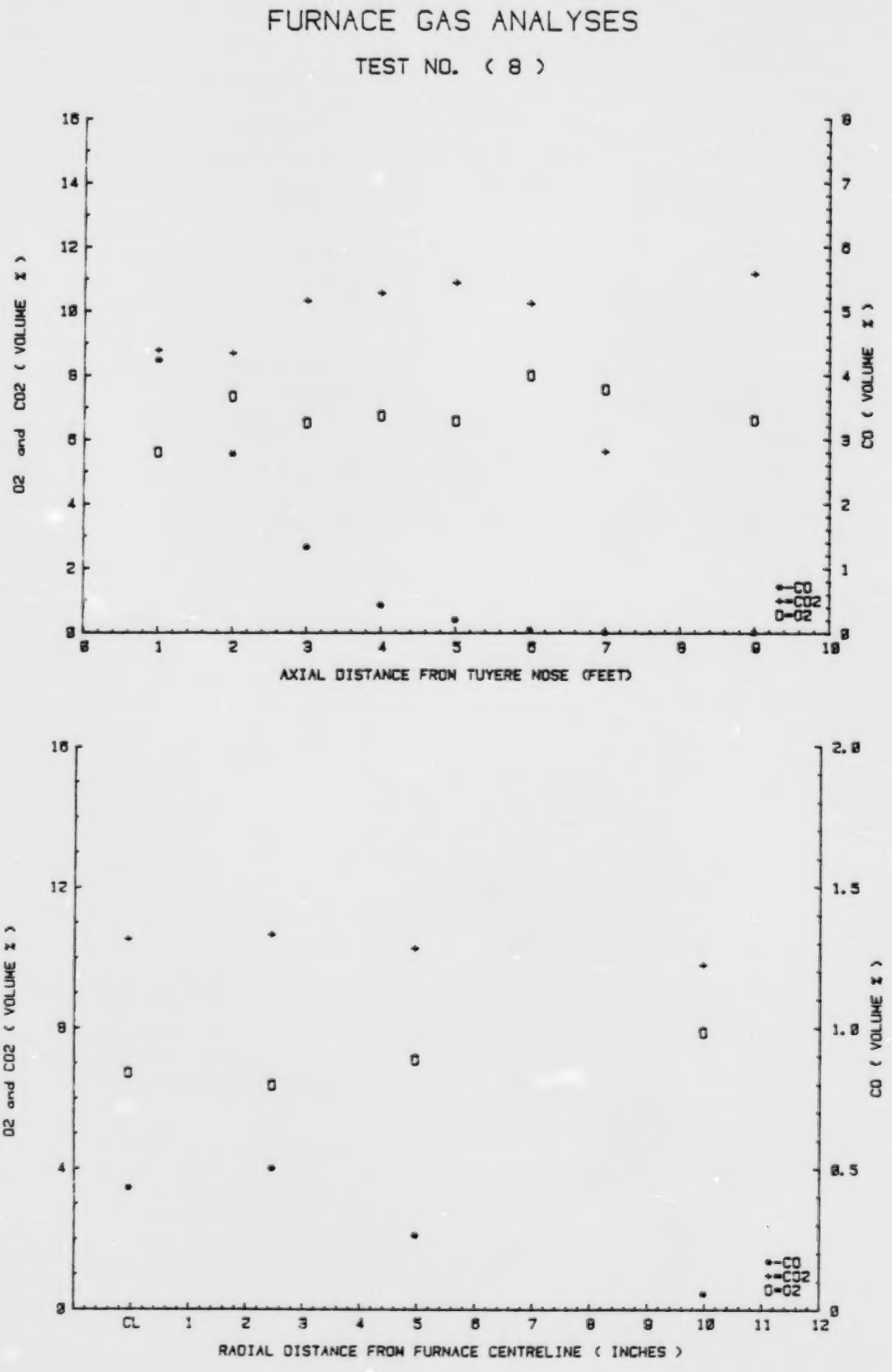

FURNACE GAS ANALYSES
TEST NO. (8)
O2 and CO2 (VOLUME %)
CO (VOLUME %)
AXIAL DISTANCE FROM TUYERE NOSE (FEET)
+-CO
+-CO2
O-O2
RADIAL DISTANCE FROM FURNACE CENTRELINE (INCHES)

Figure 12 AIII: 25 Wt % Coal (minus 100 mesh) in No 6P Oil
(4.5 lb/min Injection Rate)

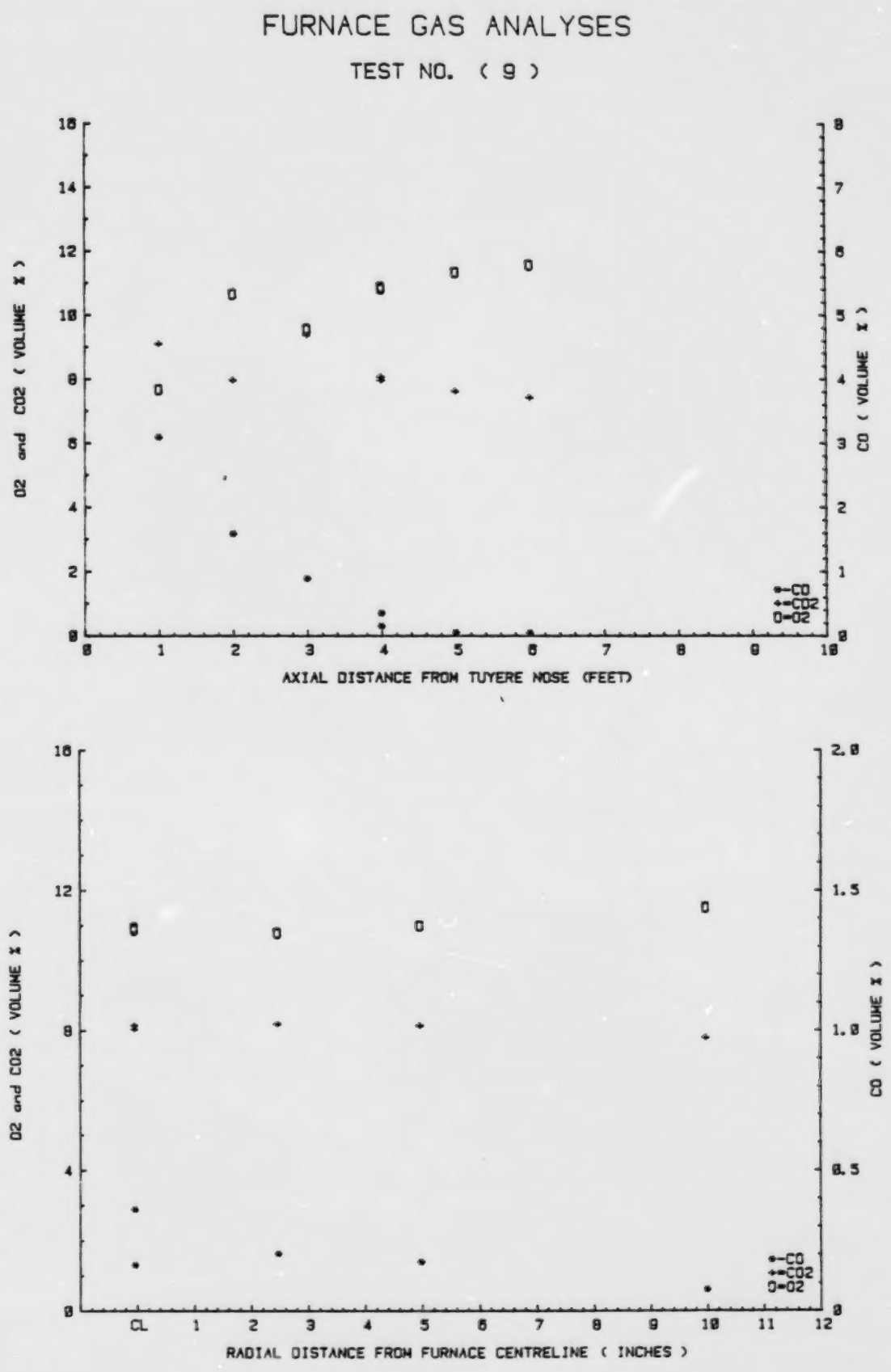


Figure 13 AIII: 25 Wt % Coal (minus 100 mesh) in No 6P Oil
(4.5 lb/min Injection Rate)

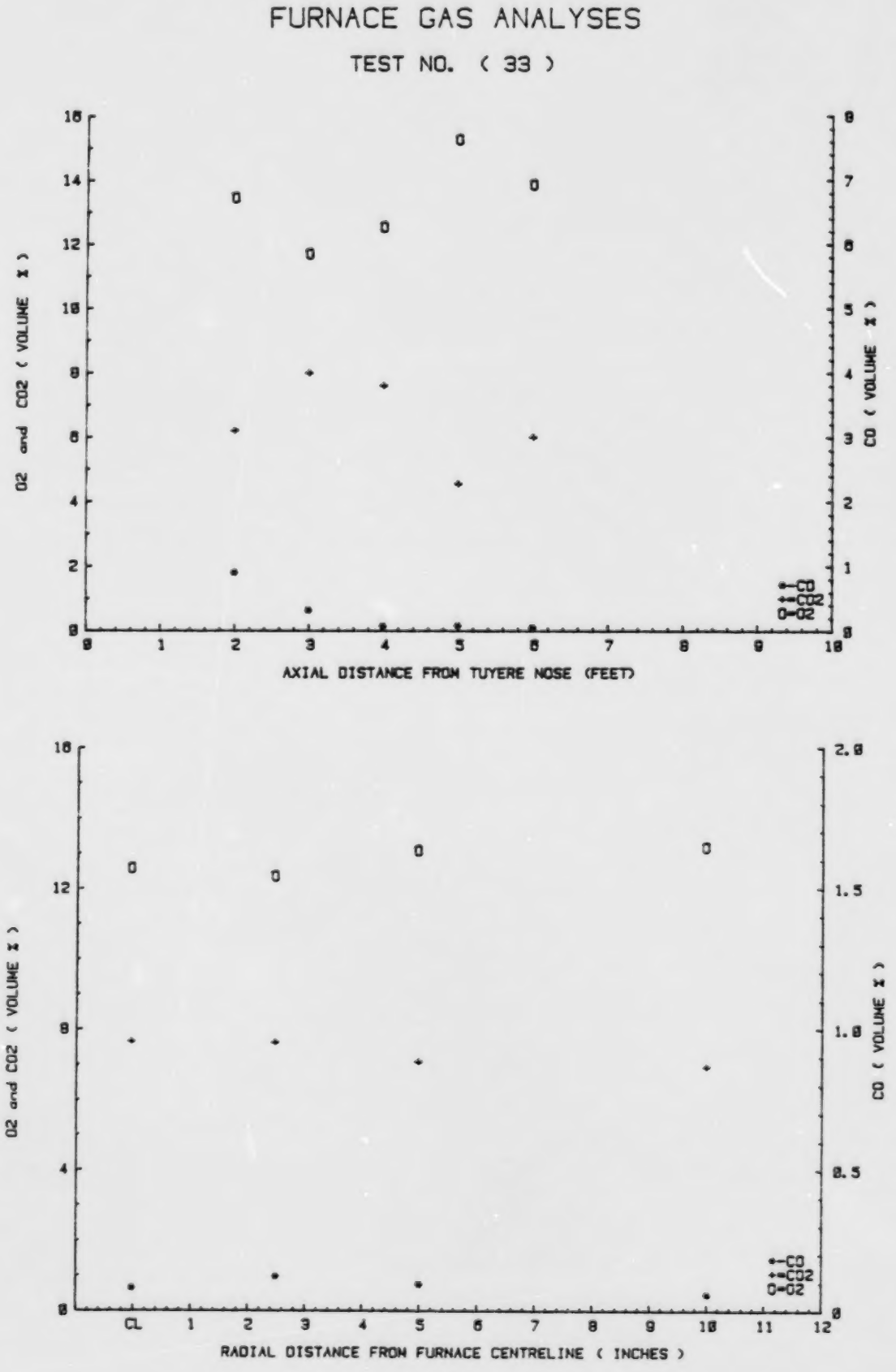


Figure 14 AIII: 25 Wt % Coal (minus 100 mesh) in No 6P Oil
(6 lb/min Injection Rate)

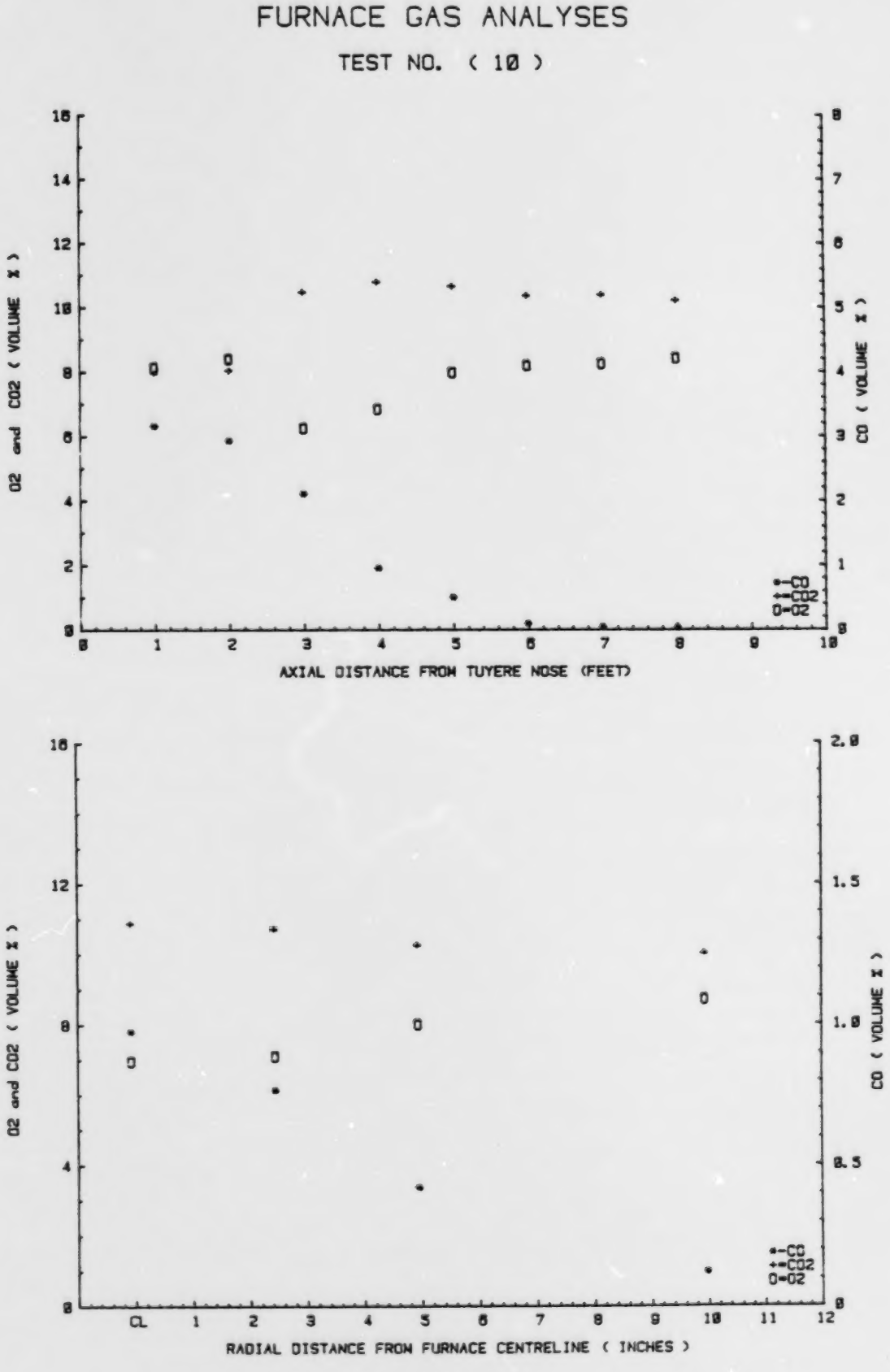

FURNACE GAS ANALYSES
TEST NO. (10)
O2 and CO2 (VOLUME %)
CO (VOLUME %)
AXIAL DISTANCE FROM TUYERE NOSE (FEET)
*-CO
+-CO2
O-O2
RADIAL DISTANCE FROM FURNACE CENTRELINE (INCHES)

Figure 15 AIII: 25 Wt % Coal (minus 100 mesh) in No 6P Oil
(6 lb/min Injection Rate)

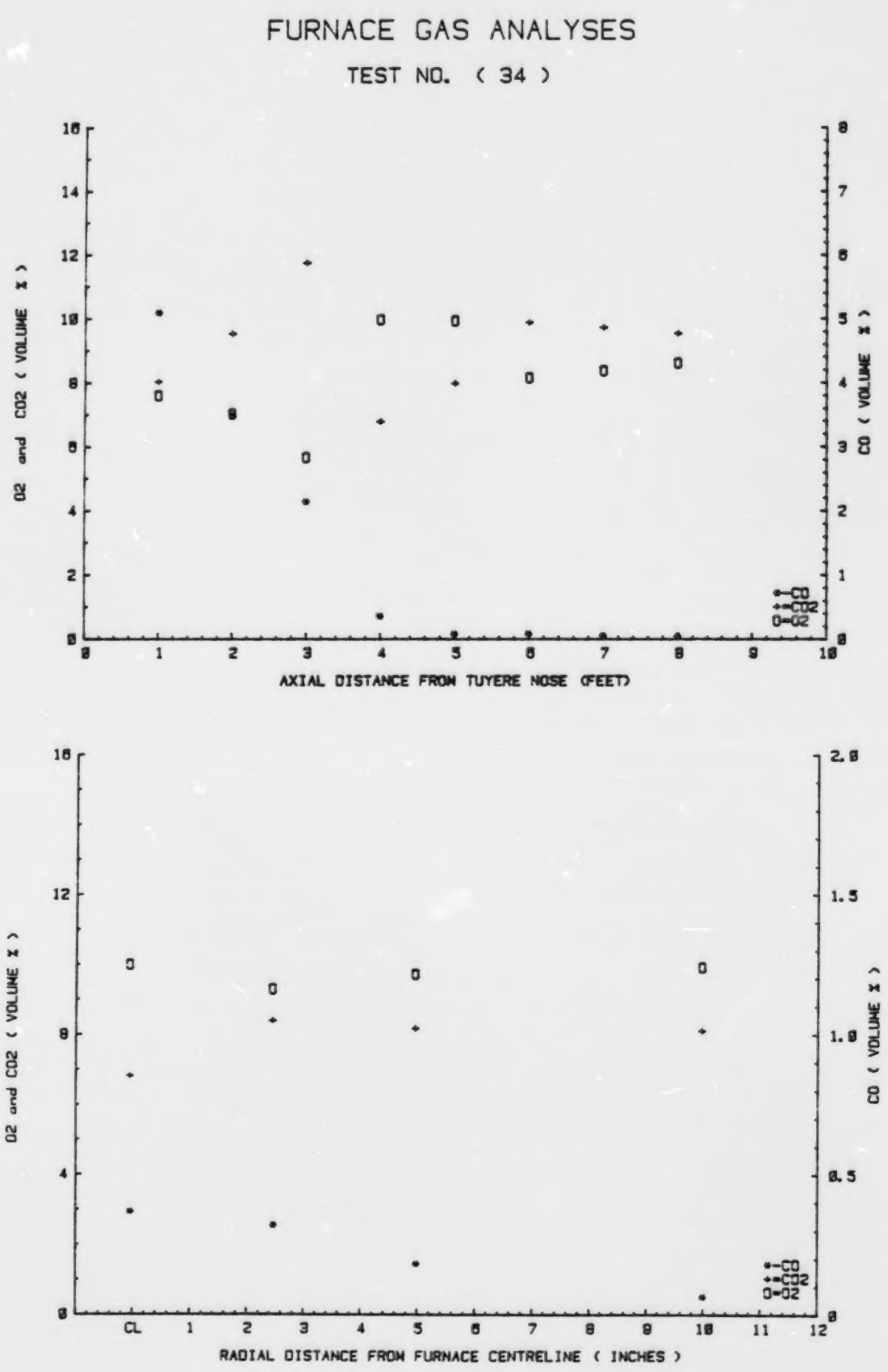

FURNACE GAS ANALYSES
TEST NO. (34)
O2 and CO2 (VOLUME %)
CO (VOLUME %)
AXIAL DISTANCE FROM TUYERE NOSE (FEET)
+-CO
*-CO2
O-O2
RADIAL DISTANCE FROM FURNACE CENTRELINE (INCHES)

Figure 16 AIII: 50 Wt % Coal (minus 100 mesh) in No 6P Oil
(4.5 lb/min Injection Rate)

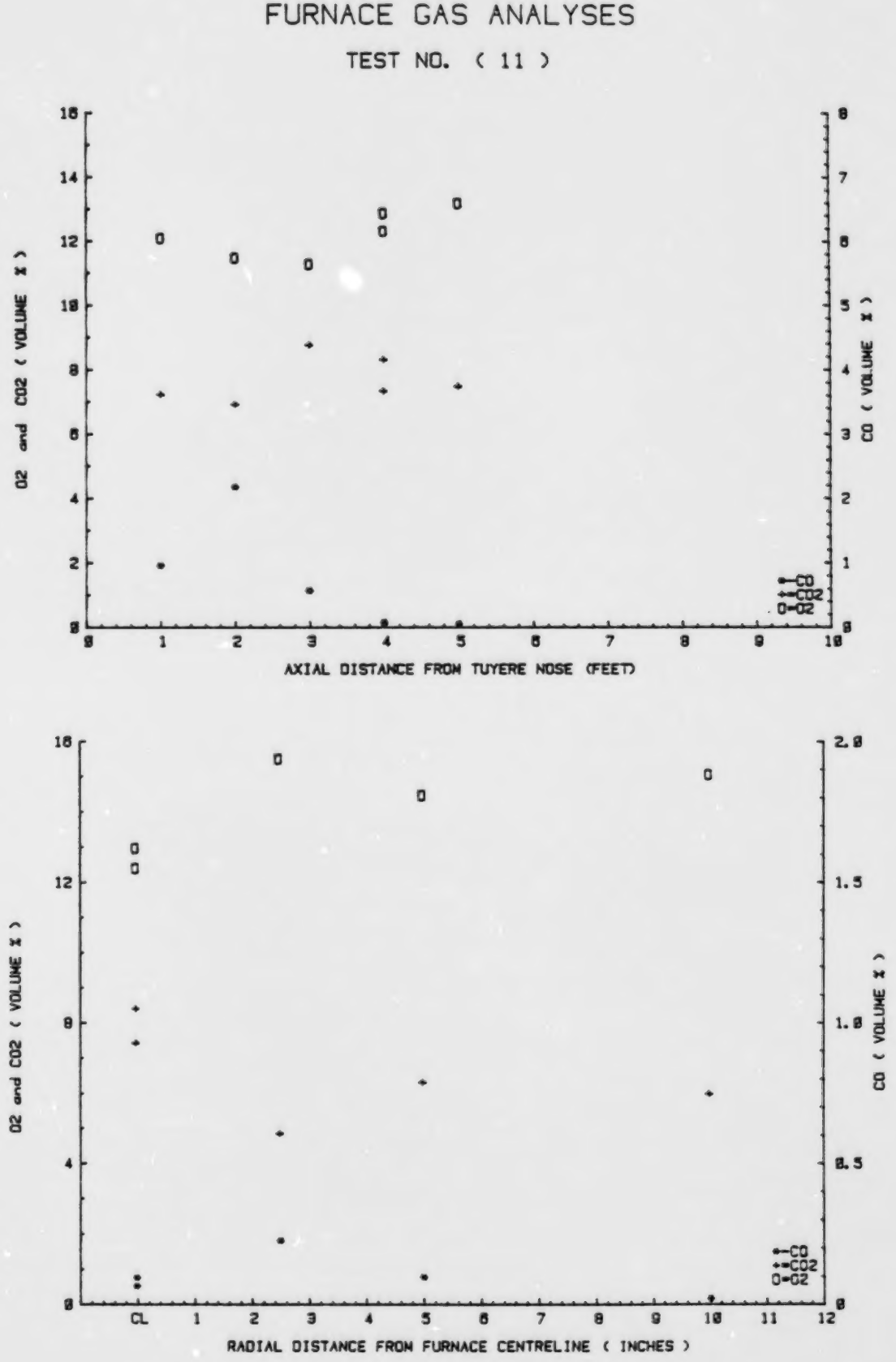

FURNACE GAS ANALYSES
TEST NO. (11)
O2 and CO2 (VOLUME %)
CO (VOLUME %)
AXIAL DISTANCE FROM TUYERE NOSE (FEET)
CO
CO2
O2
RADIAL DISTANCE FROM FURNACE CENTRELINE (INCHES)

Figure 17 AIII: 50 Wt % Coal (minus 100 mesh) in No 6P Oil
(4.5 lb/min Injection Rate)

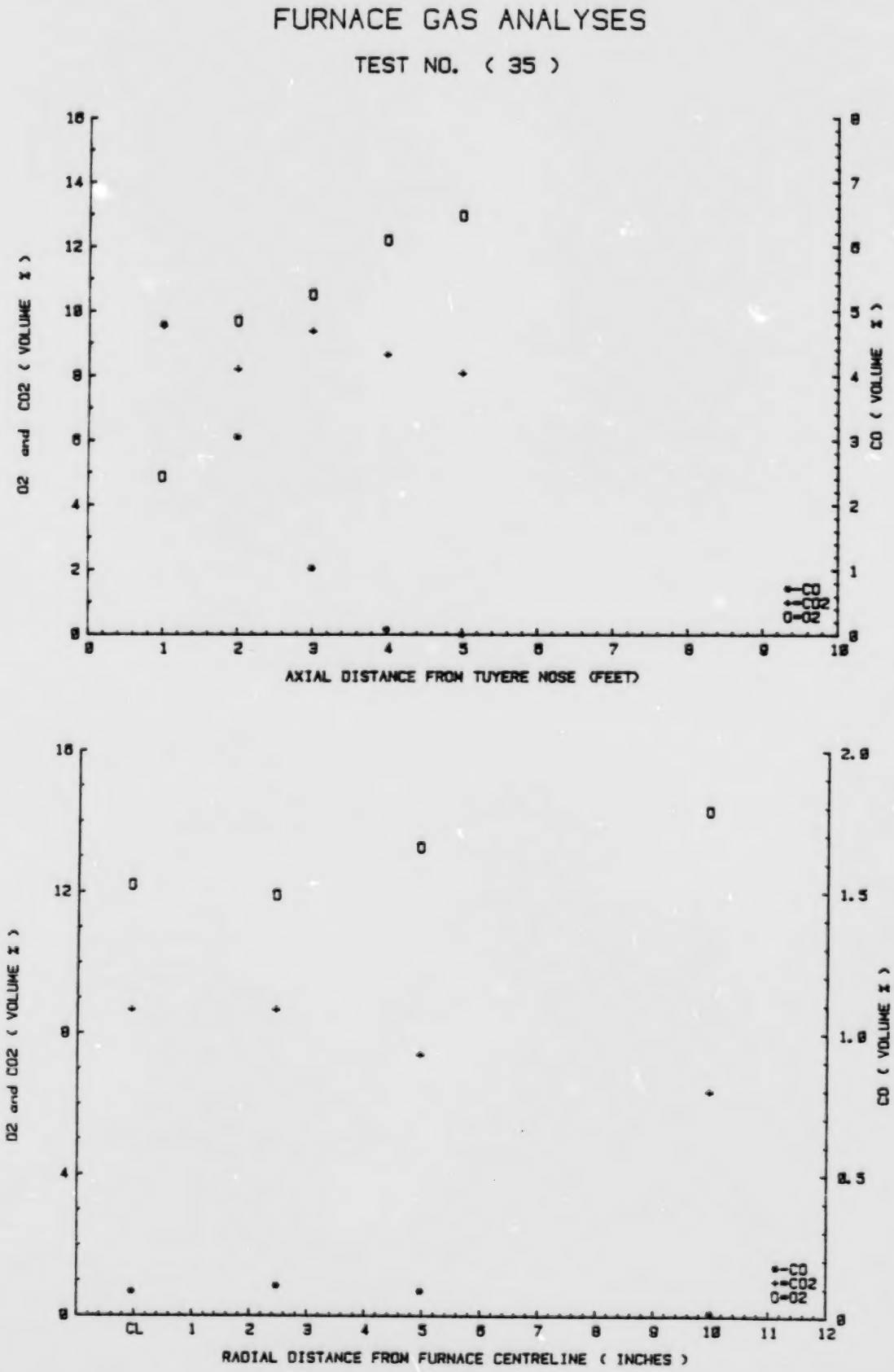


Figure 18 AIII: 50 Wt % Coal (minus 100 mesh) in No 6P Oil
(6 lb/min Injection Rate)

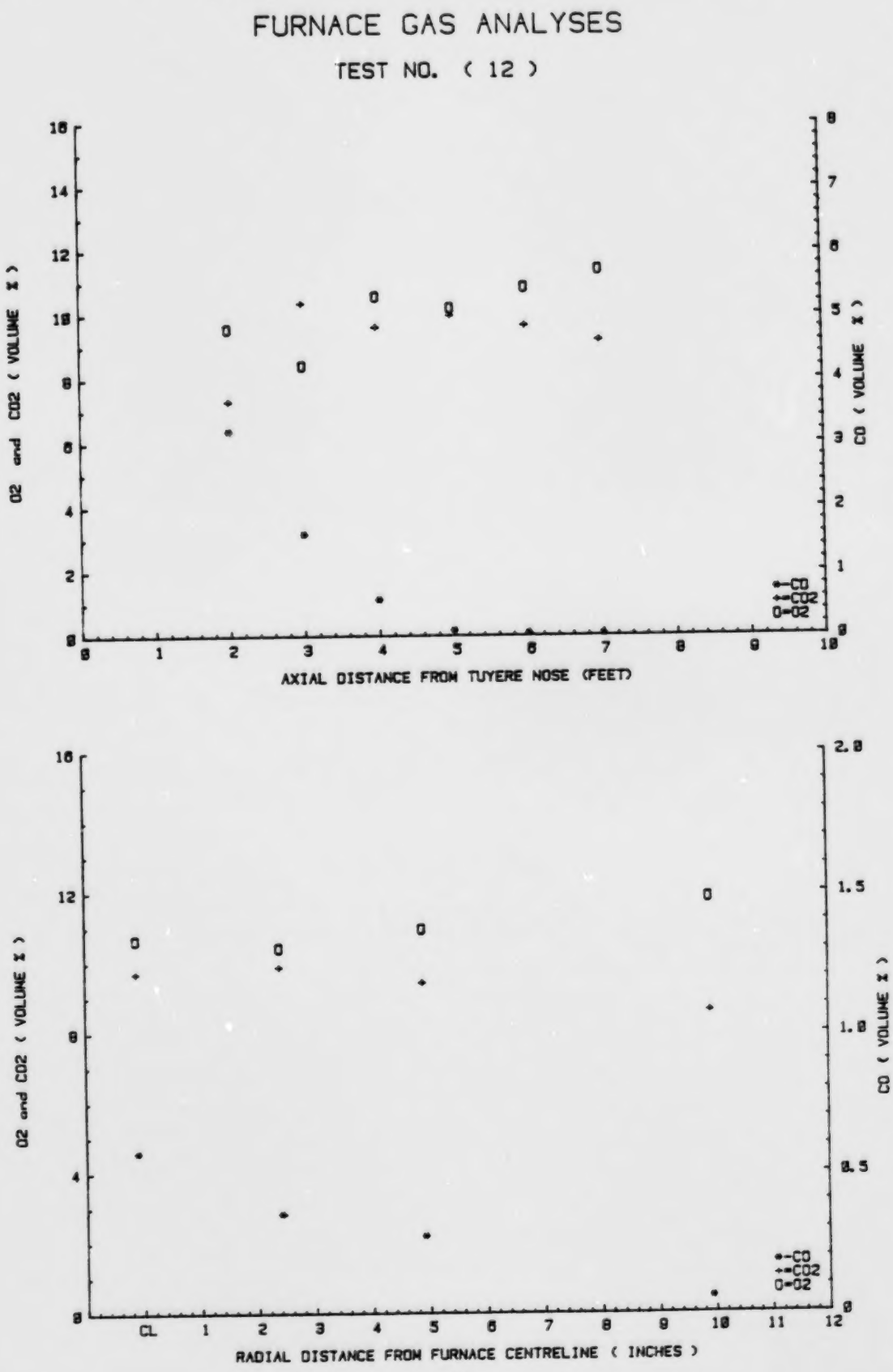


Figure 19 AIII: 50 Wt % Coal (minus 100 mesh) in No 6P Oil
(6 lb/min Injection Rate)

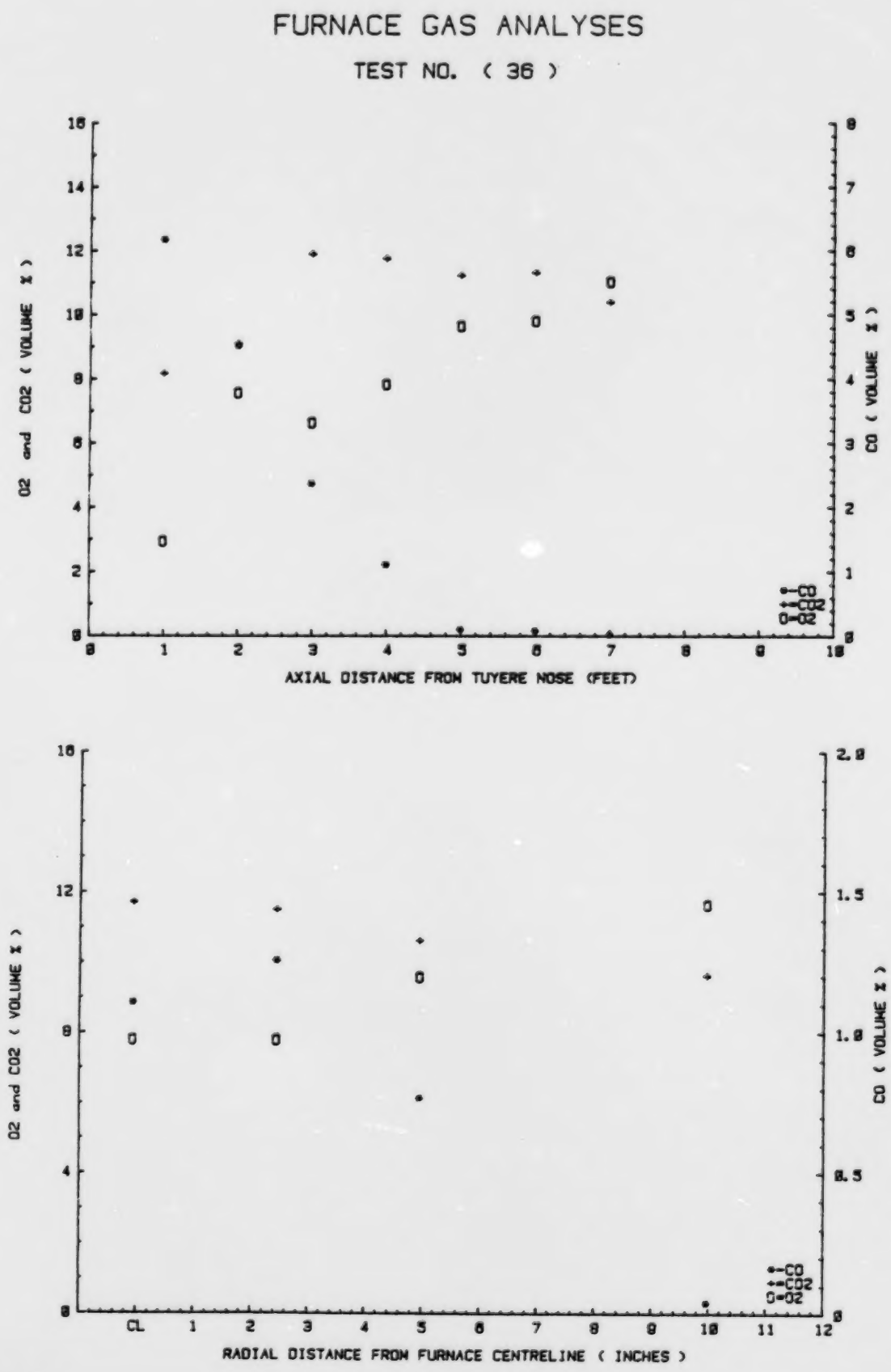
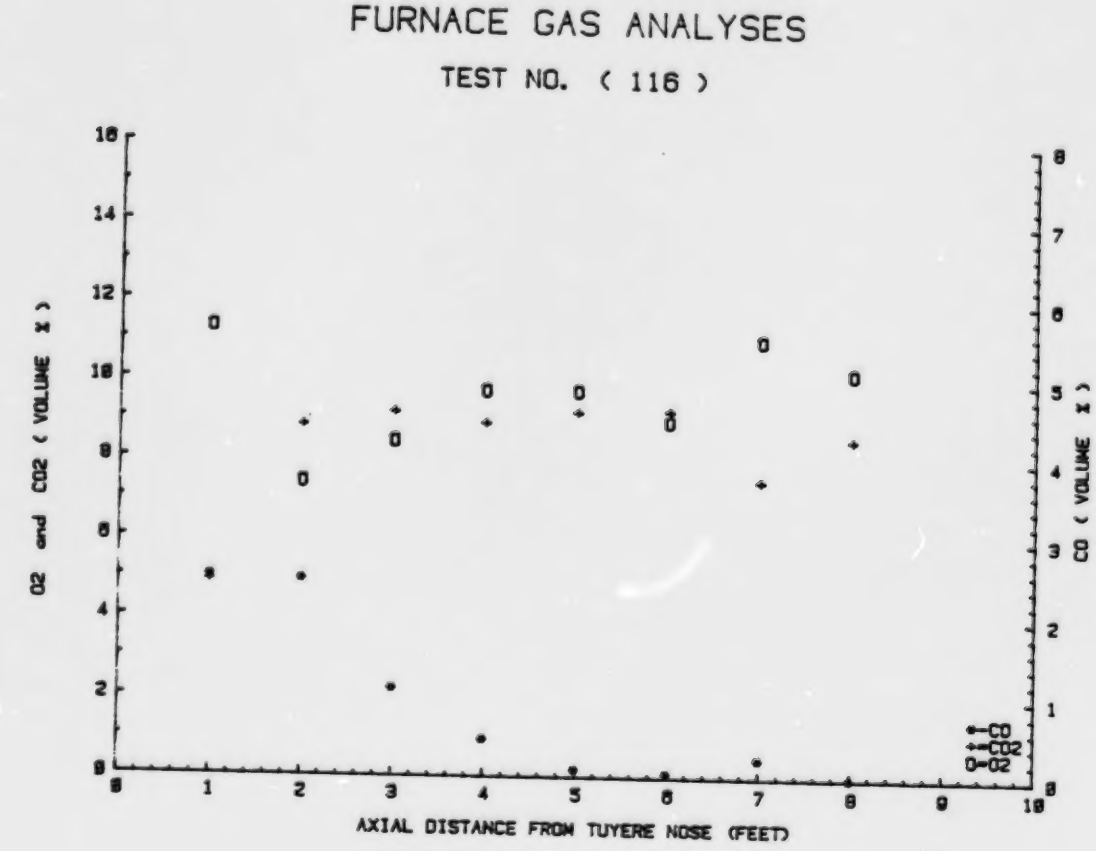


Figure 20 AIII: 65 Wt % Coal (minus 100 mesh) in No 6P Oil
(6 lb/min Injection Rate)



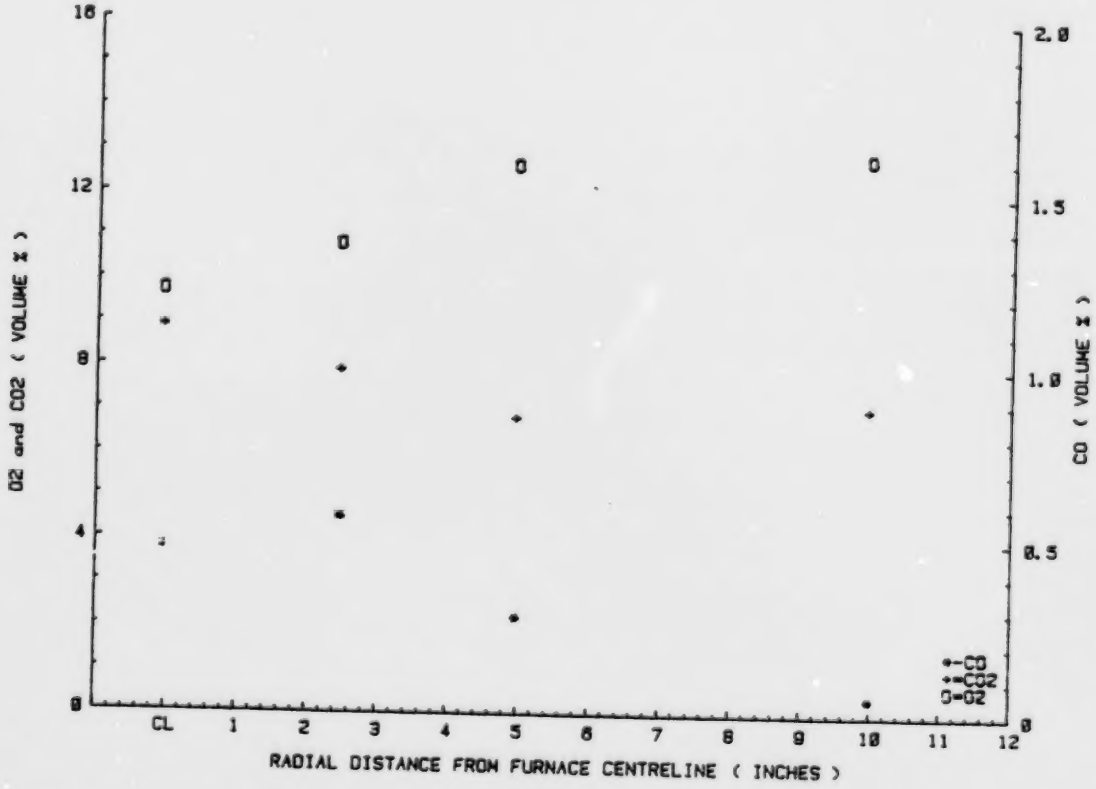


Figure 21 AIII: 65 Wt % Coal (minus 100 mesh) in No 6P Oil
(6 lb/min Injection Rate)

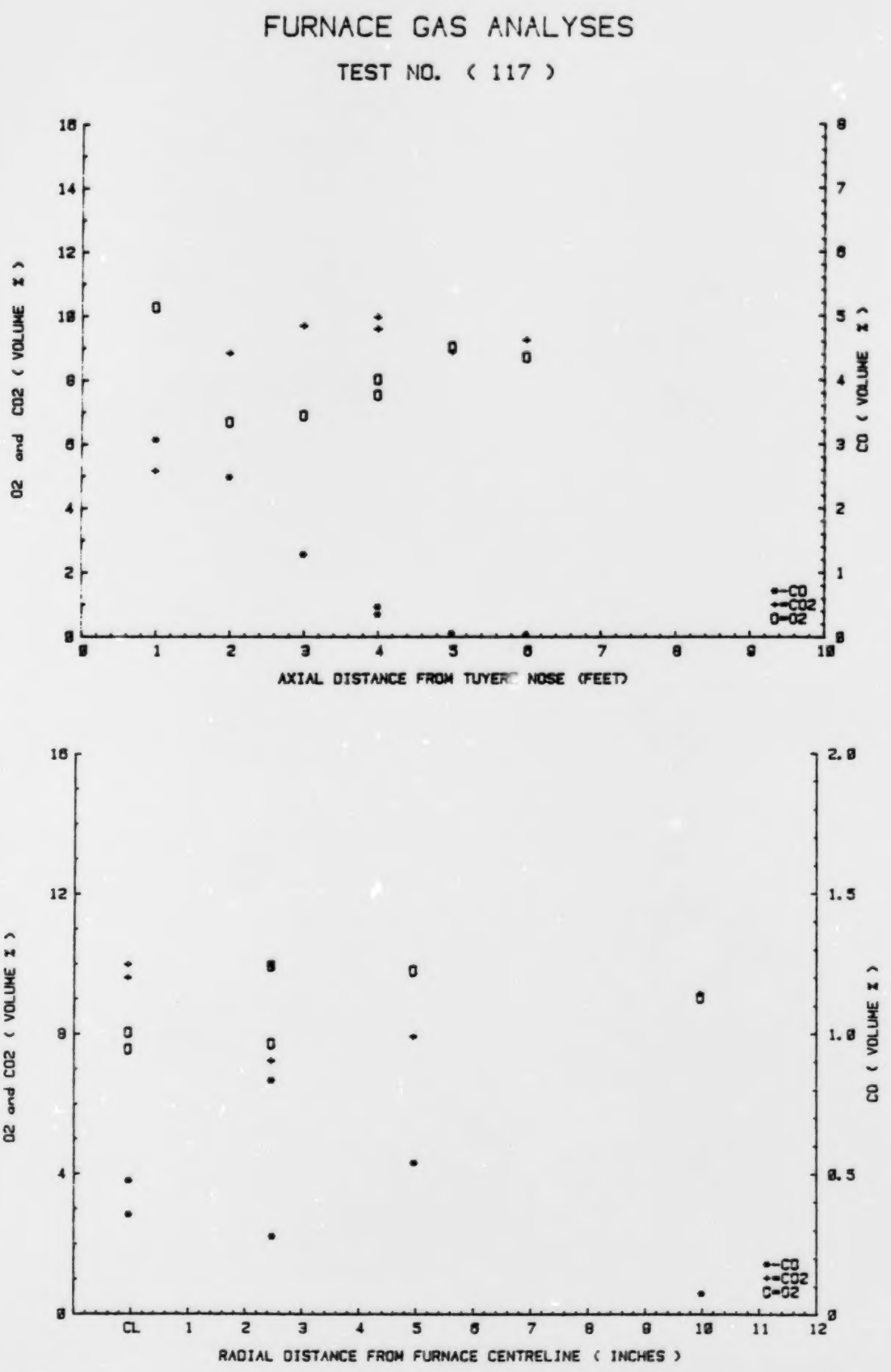

FURNACE GAS ANALYSES
TEST NO. (117)
O2 and CO2 (VOLUME %)
CO (VOLUME %)
AXIAL DISTANCE FROM TUYERE NOSE (FEET)
+-CO
+-CO2
O-O2
RADIAL DISTANCE FROM FURNACE CENTRELINE (INCHES)

Figure 22 AIII: 25 Wt % Coal (minus 35 mesh) in No 6P Oil
(4.5 lb/min Injection Rate)

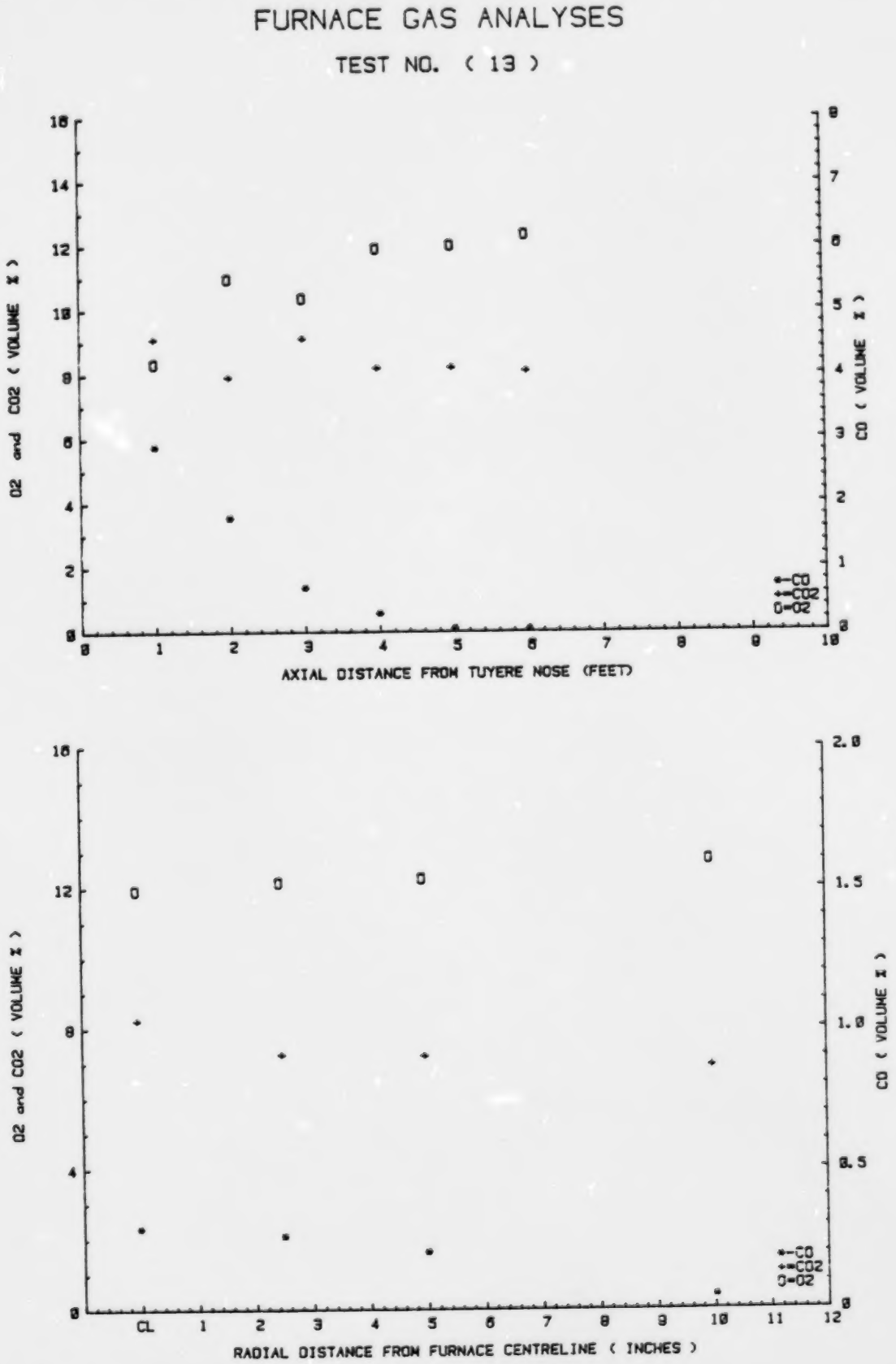


Figure 23 AIII: 25 Wt % Coal (minus 35 mesh) in No 6P Oil
(4.5 lb/min Injection Rate)

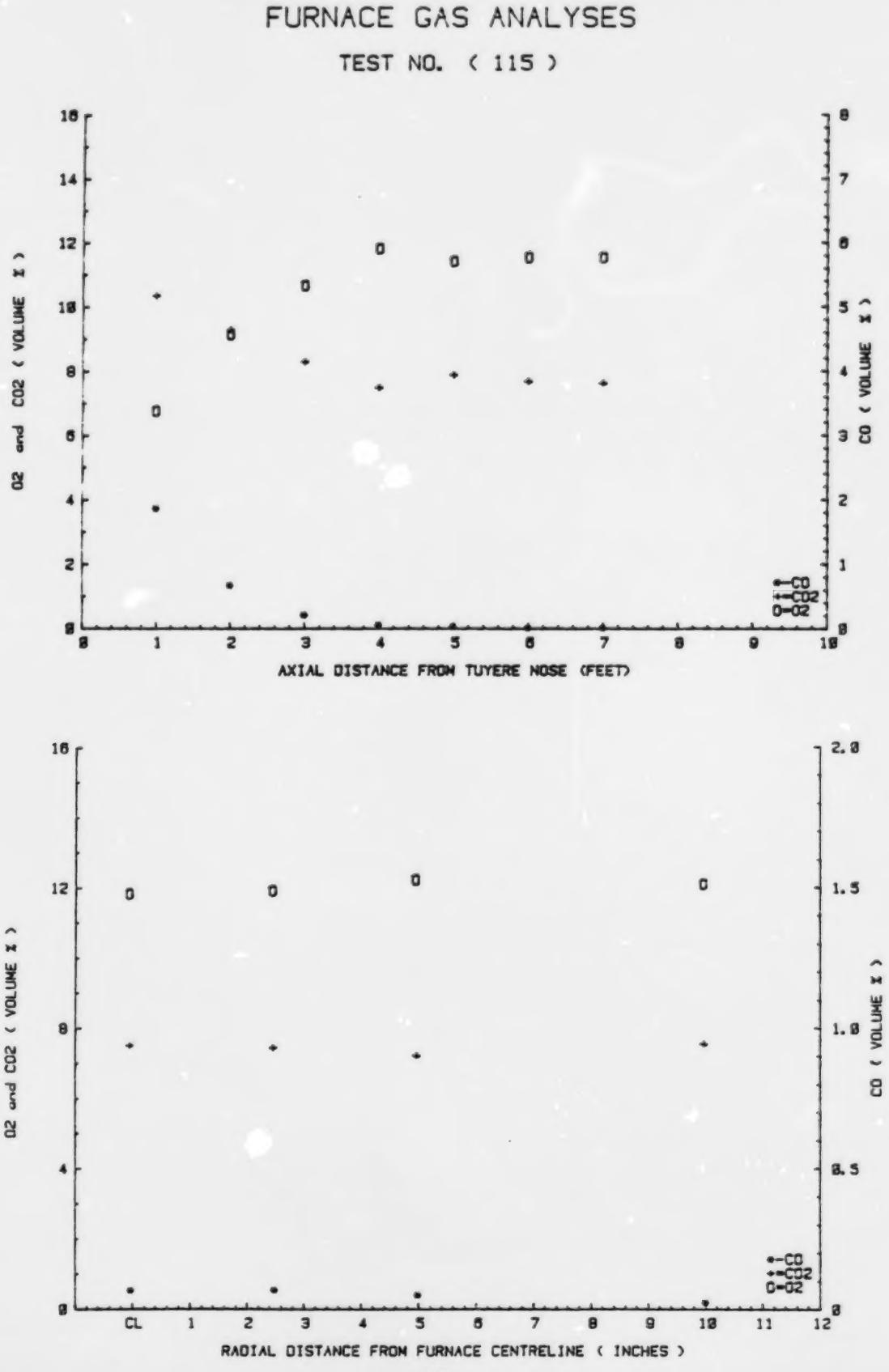

FURNACE GAS ANALYSES
TEST NO. (115)
O2 and CO2 (VOLUME %)
CO (VOLUME %)
AXIAL DISTANCE FROM TUYERE NOSE (FEET)
CO
CO2
O2
RADIAL DISTANCE FROM FURNACE CENTRELINE (INCHES)

Figure 24 AIII: 25 Wt % Coal (minus 35 mesh) in No 6P Oil
(6 lb/min Injection Rate)

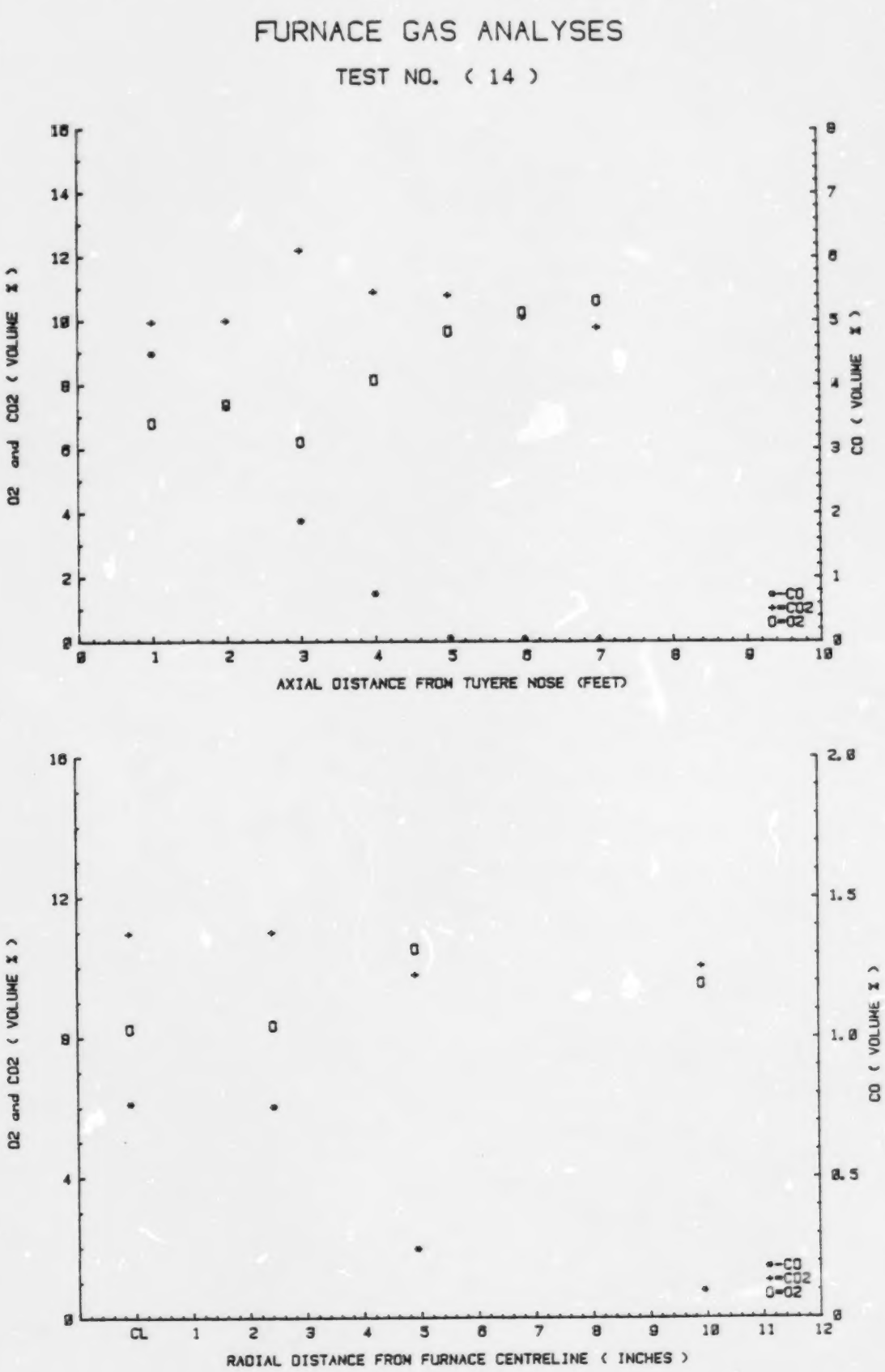


Figure 25 AIII: 25 Wt % Coal (minus 35 mesh) in No 6P Oil
(6 lb/min Injection Rate)

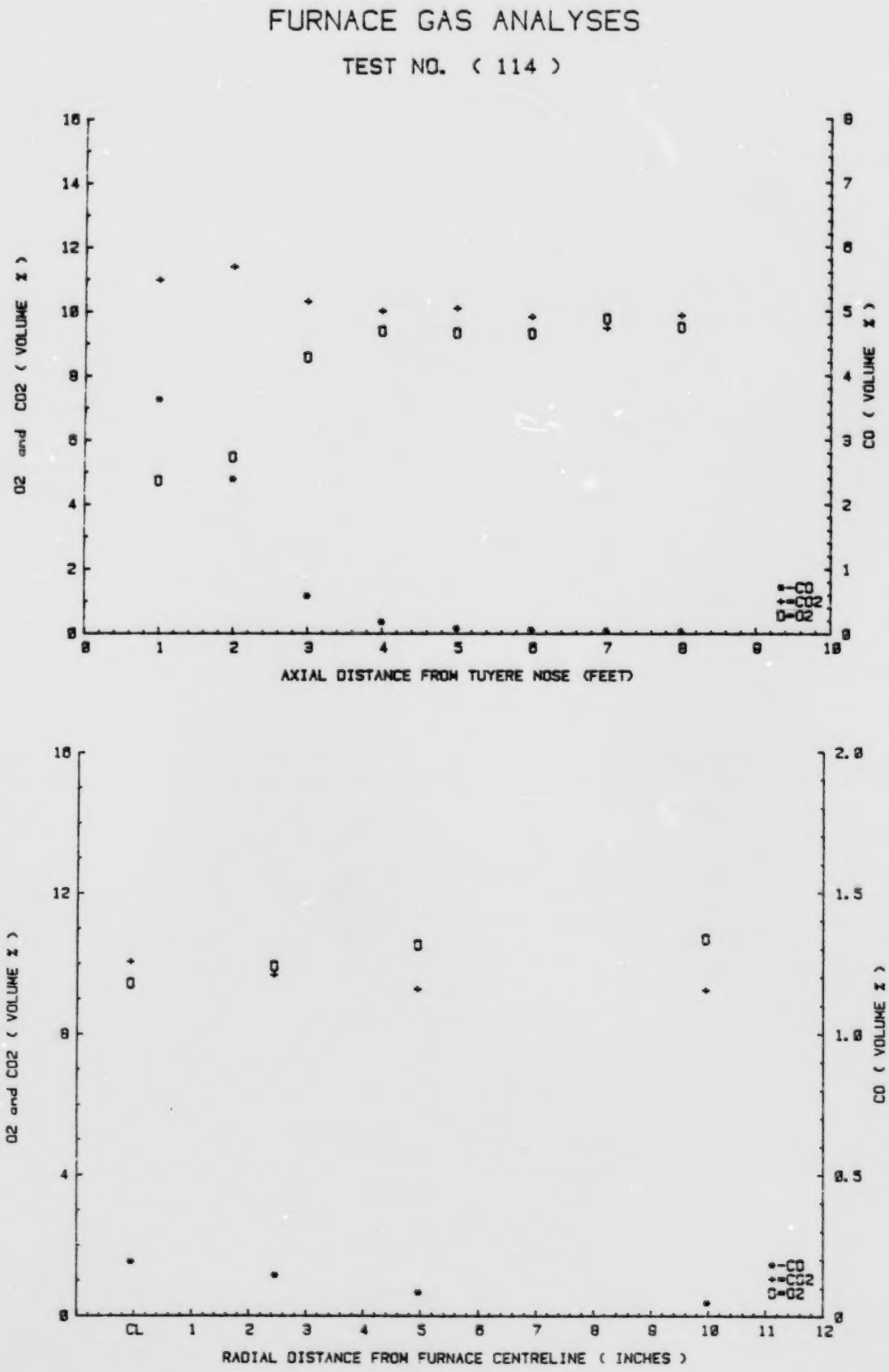

FURNACE GAS ANALYSES
TEST NO. (114)
O2 and CO2 (VOLUME %)
CO (VOLUME %)
AXIAL DISTANCE FROM TUYERE NOSE (FEET)
•-CO
+-CO2
O-O2
RADIAL DISTANCE FROM FURNACE CENTRELINE (INCHES)

Figure 26 AIII: 50 Wt % Coal (minus 35 mesh) in No 6P Oil
(4.5 lb/min Injection Rate)

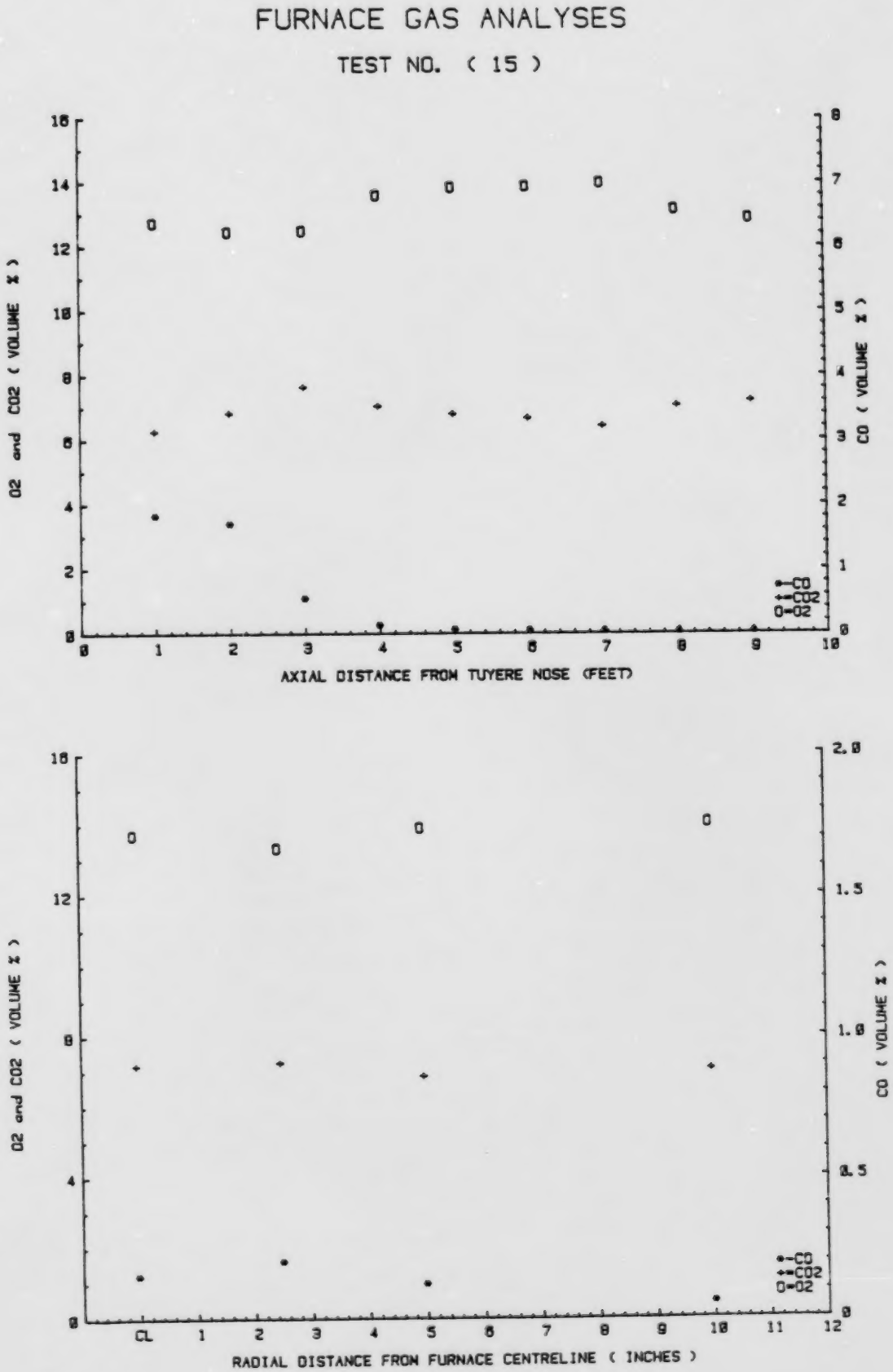


Figure 27 AIII: 50 Wt % Coal (minus 35 mesh) in No 6P Oil
(4.5 lb/min Injection Rate)

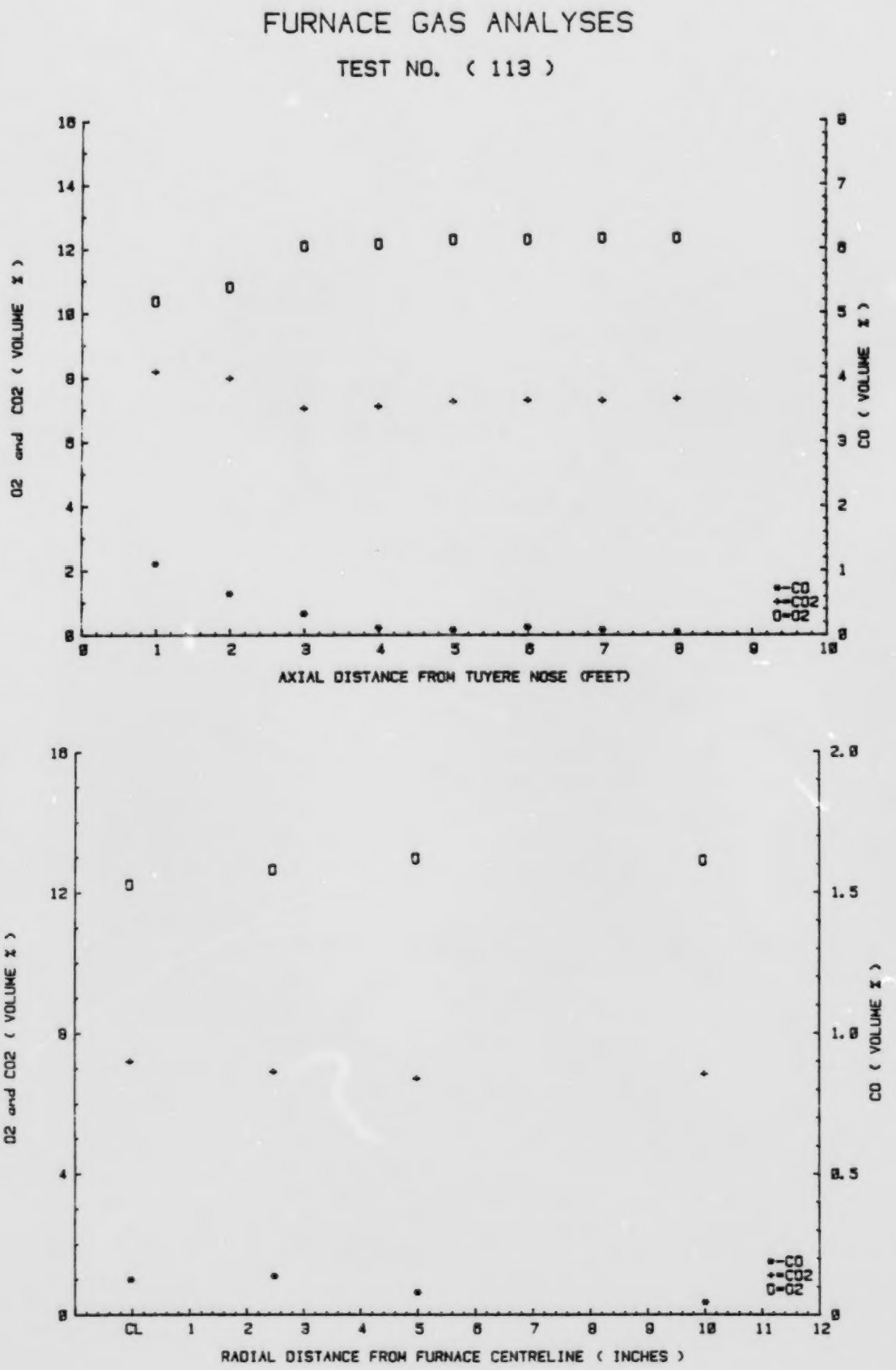


Figure 28 AIII: 50 Wt % Coal (minus 35 mesh) in No 6P Oil
(6 lb/min Injection Rate)

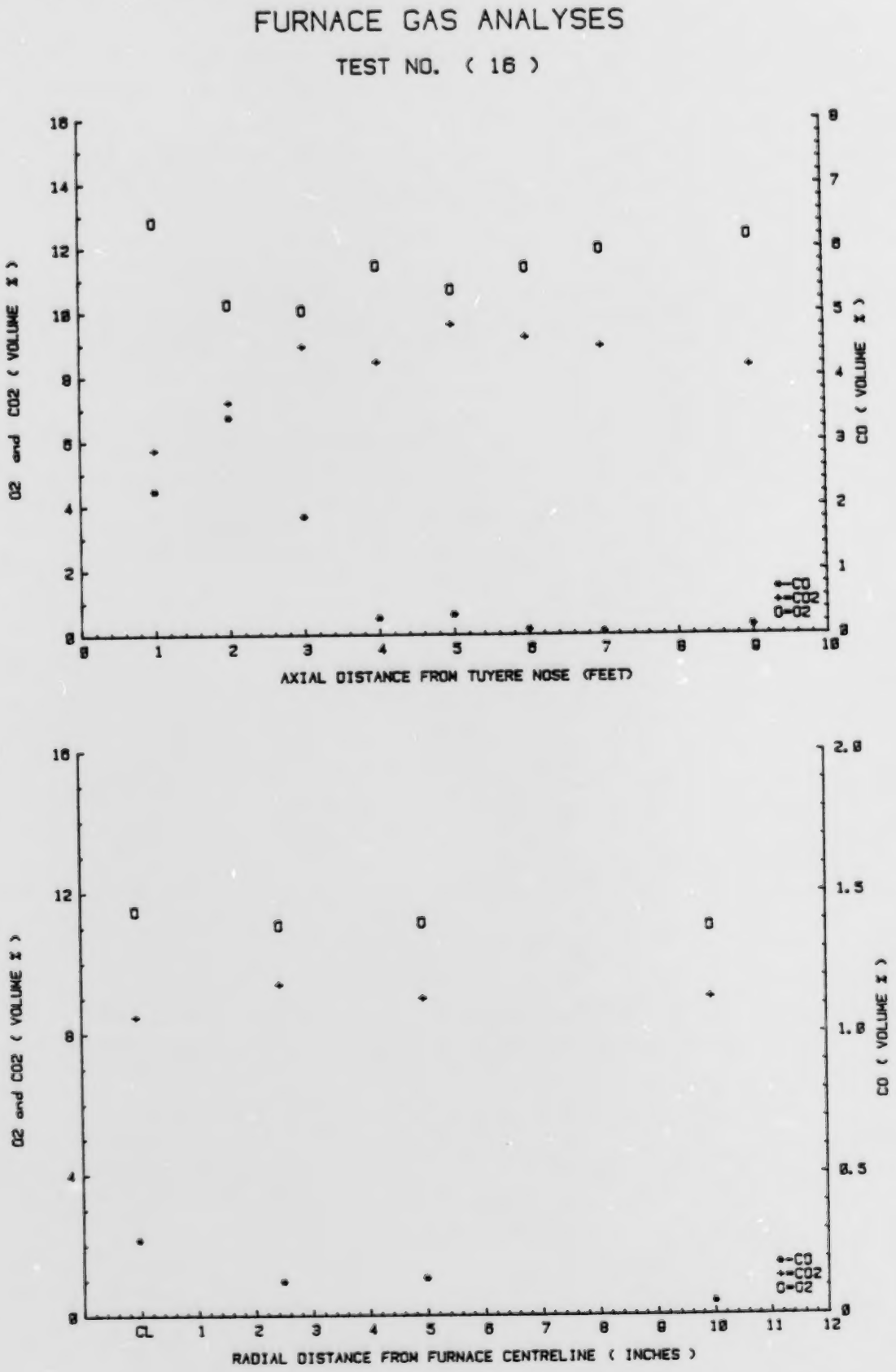


Figure 29 AIII: 50 Wt % Coal (minus 35 mesh) in No 6P Oil
(6 lb/min Injection Rate)

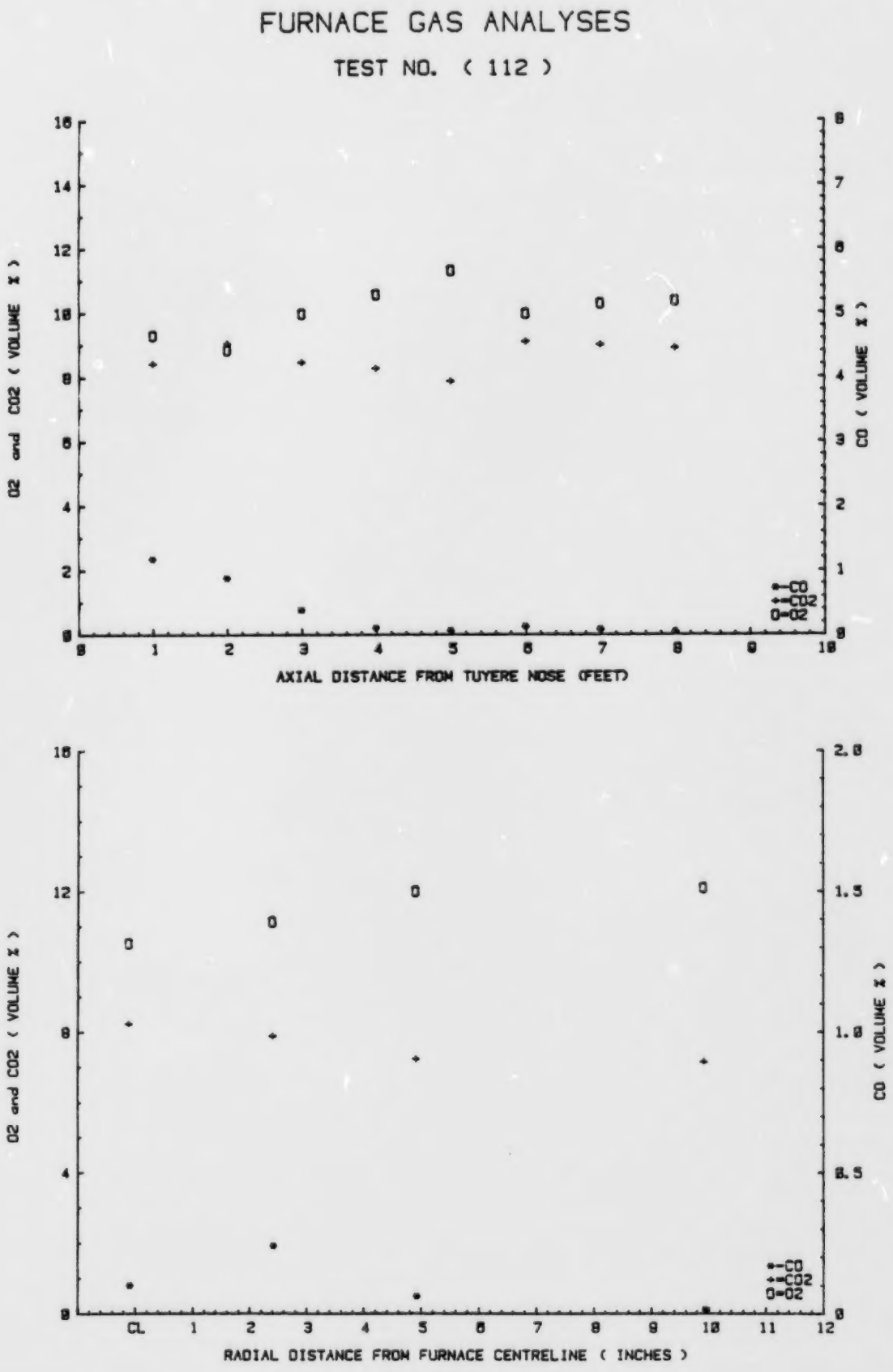

FURNACE GAS ANALYSES
TEST NO. (112)
O2 and CO2 (VOLUME %)
CO (VOLUME %)
AXIAL DISTANCE FROM TUYERE NOSE (FEET)
*-CO
+-CO2
O-O2
RADIAL DISTANCE FROM FURNACE CENTRELINE (INCHES)

Figure 30 AIII: 65 Wt % Coal (minus 35 mesh) in No 6P Oil
(6 lb/min Injection Rate)

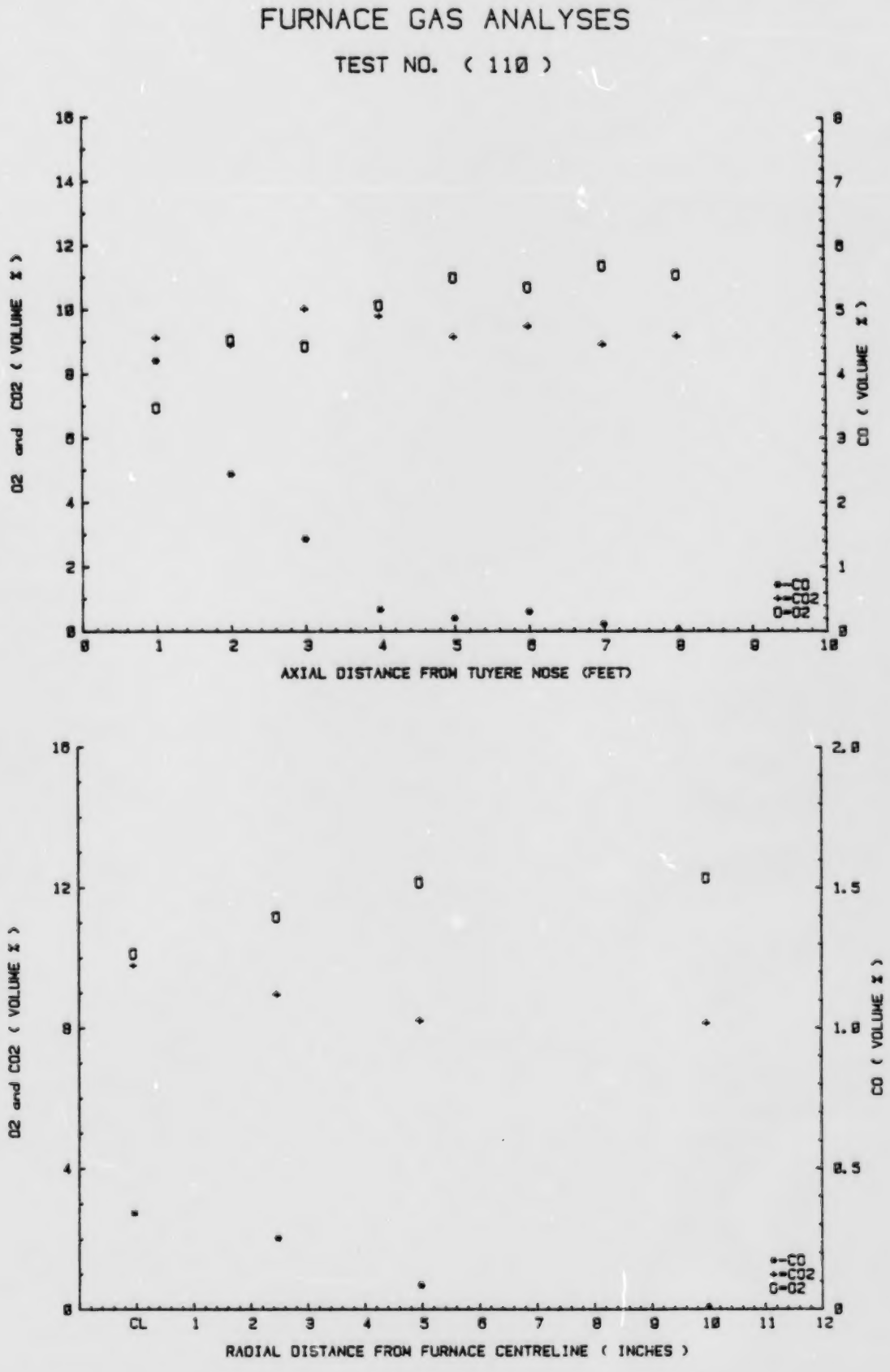


Figure 31 AIII: 65 Wt % Coal (minus 35 mesh) in No 6P Oil
(6 lb/min Injection Rate)

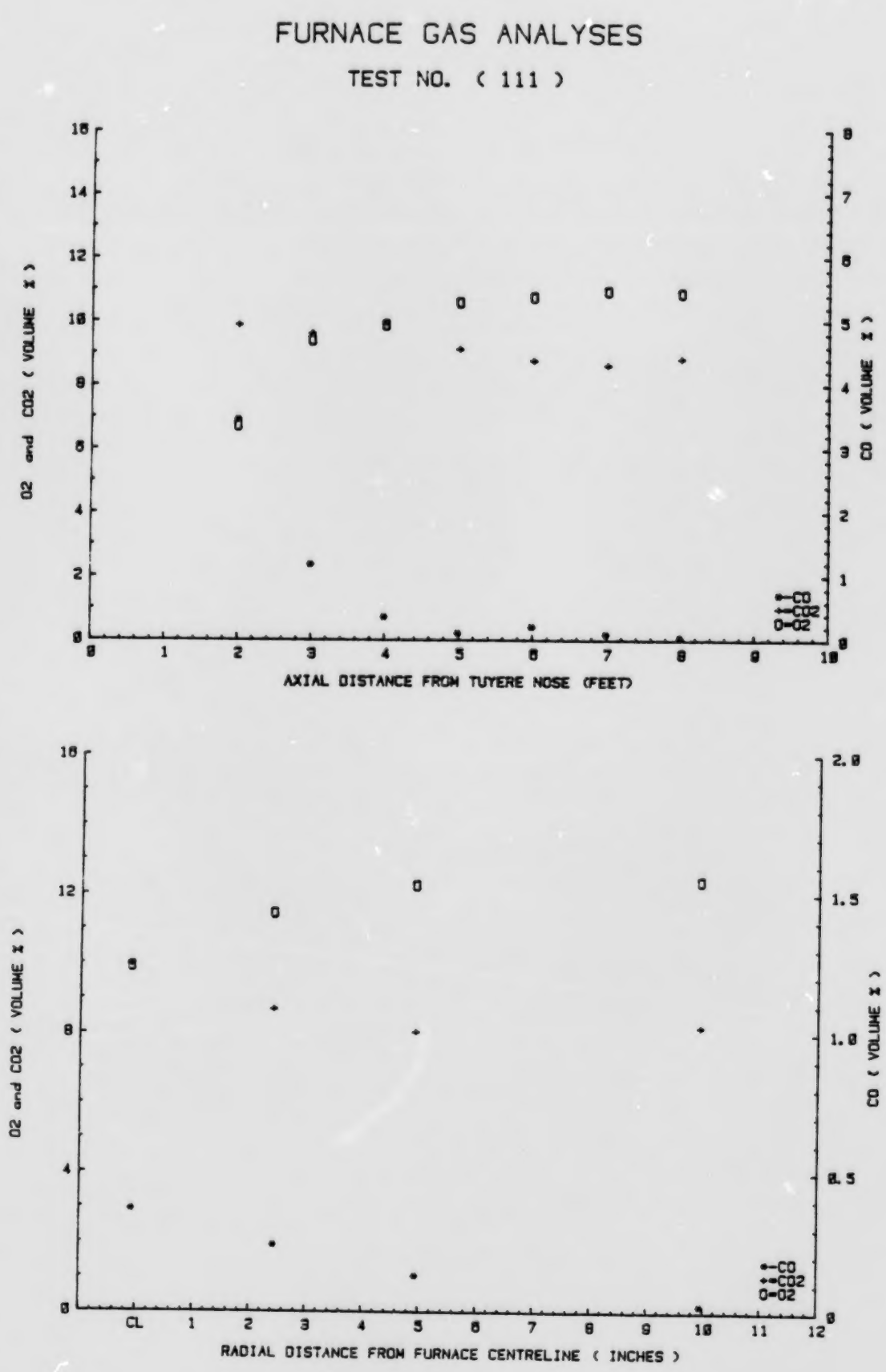

FURNACE GAS ANALYSES
TEST NO. (111)
O2 and CO2 (VOLUME %)
CO (VOLUME %)
AXIAL DISTANCE FROM TUYERE NOSE (FEET)
CO
CO2
O2
RADIAL DISTANCE FROM FURNACE CENTRELINE (INCHES)

Figure 32 AIII: 25 Wt % Coal (minus 10 mesh) in No 6P Oil
(4.5 lb/min Injection Rate)

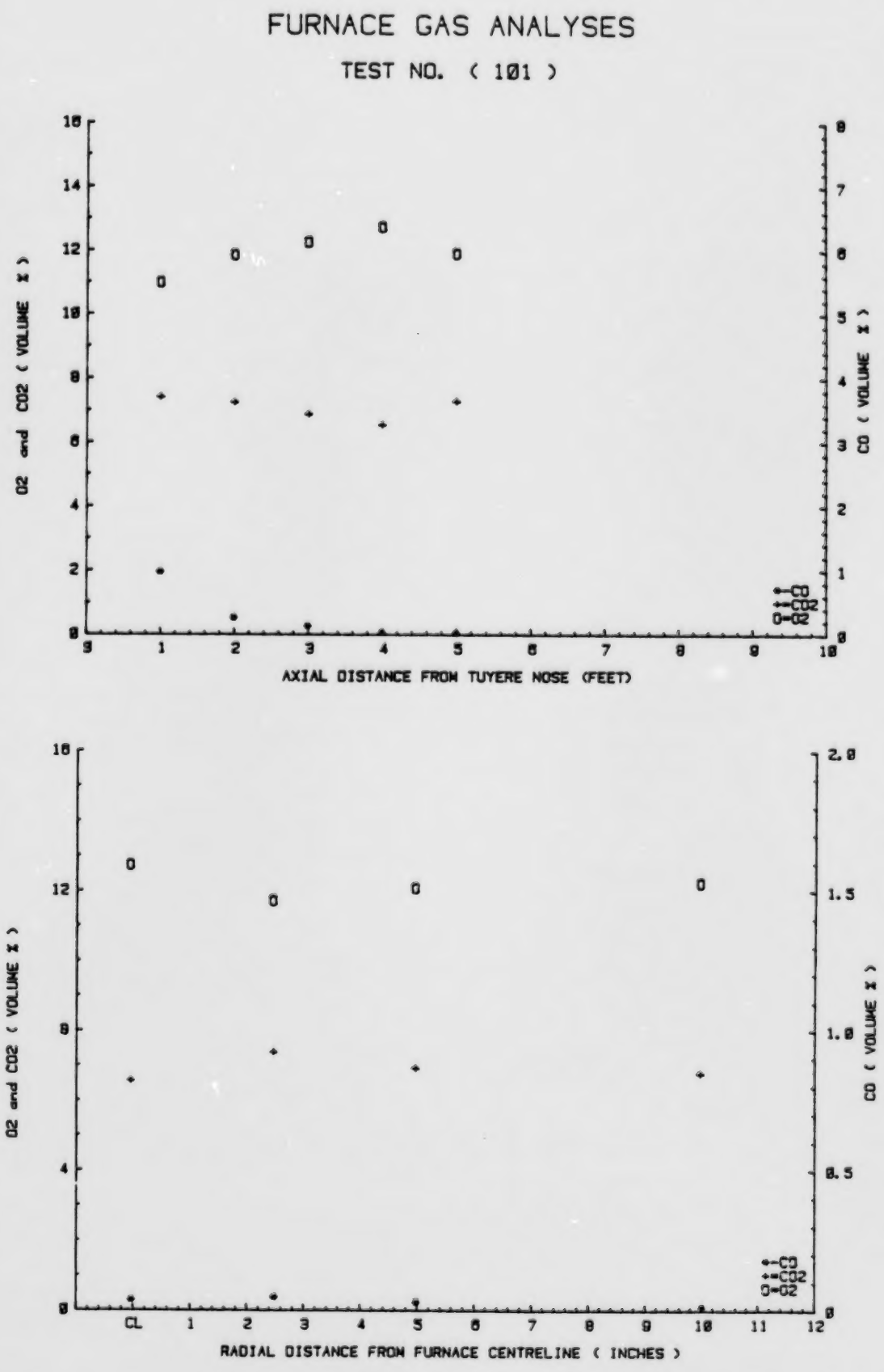


Figure 33 AIII: 25 Wt % Coal (minus 10 mesh) in No 6P Oil
(4.5 lb/min Injection Rate)

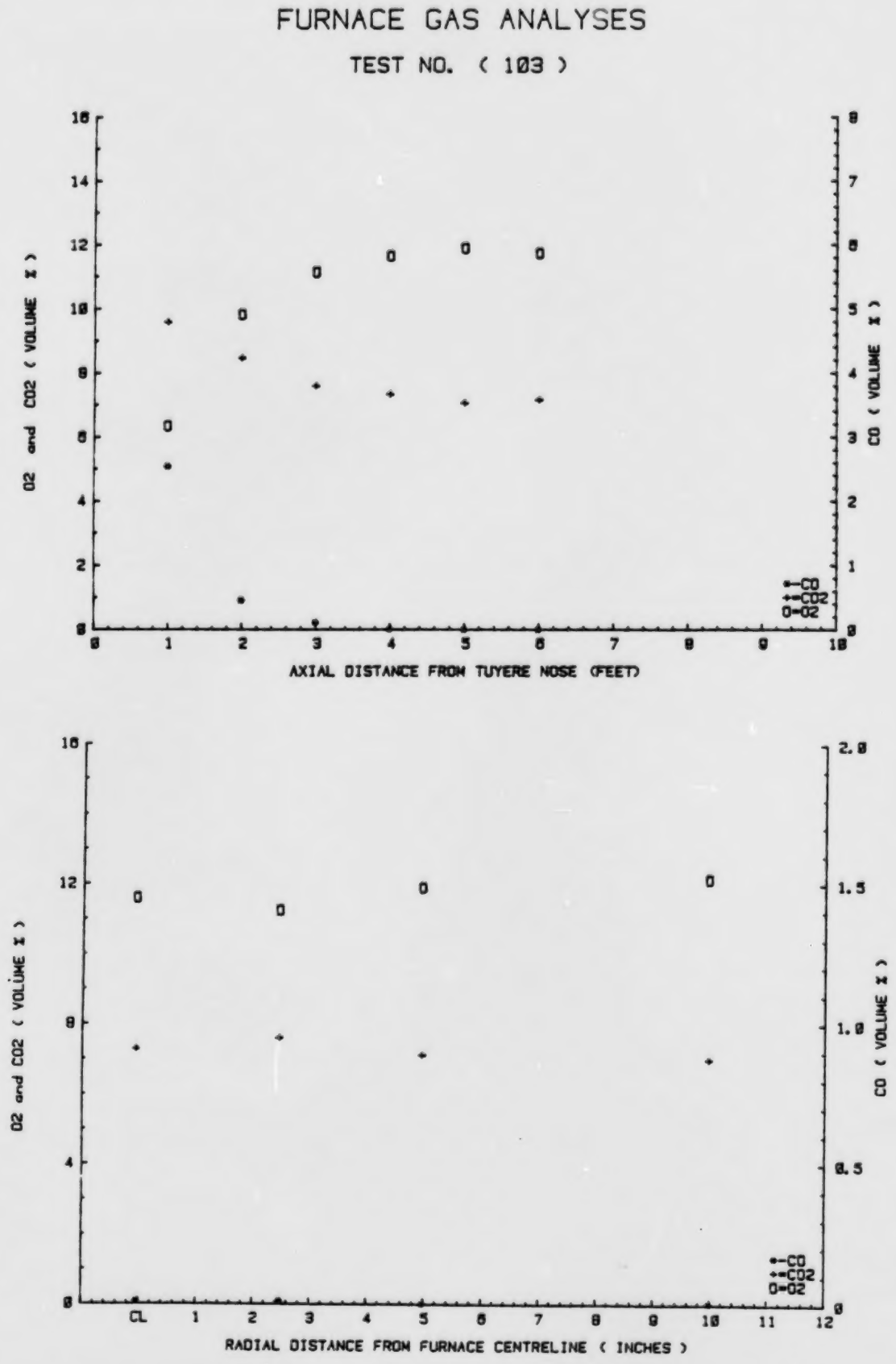
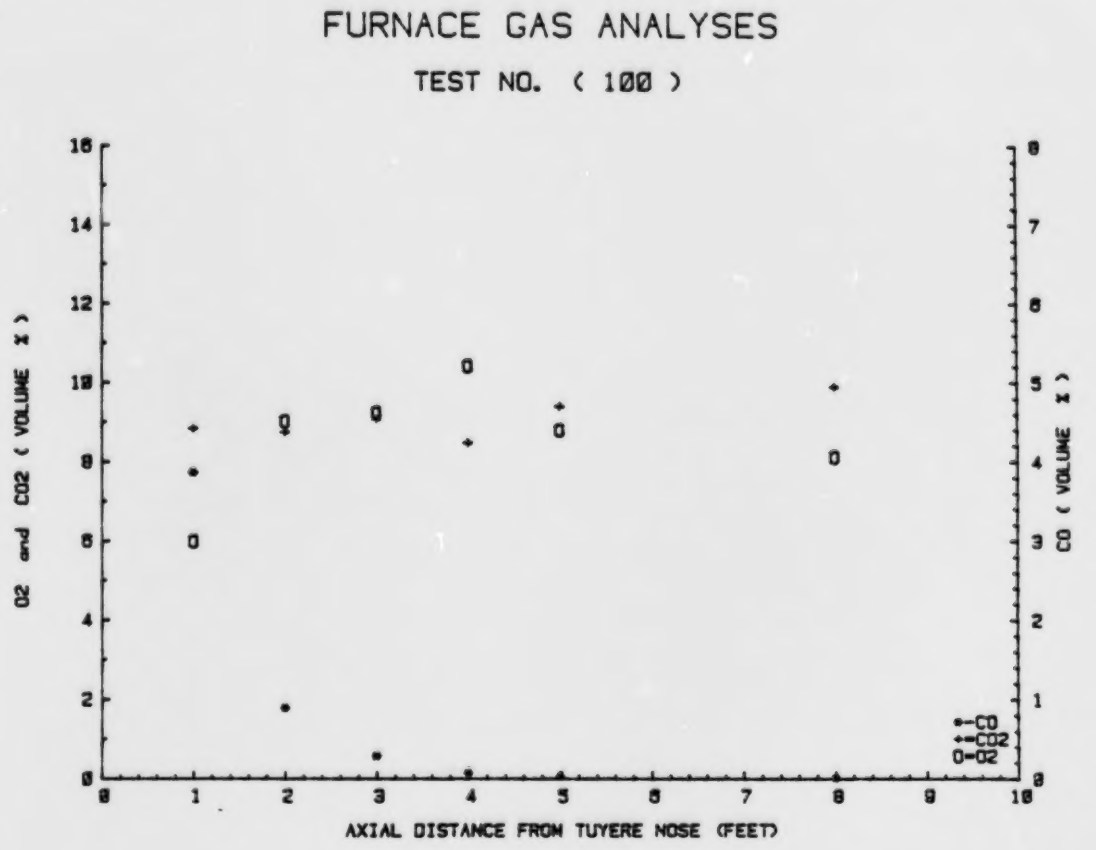


Figure 34 AIII: 25 Wt % Coal (minus 10 mesh) in No 6P Oil
(6 lb/min Injection Rate)



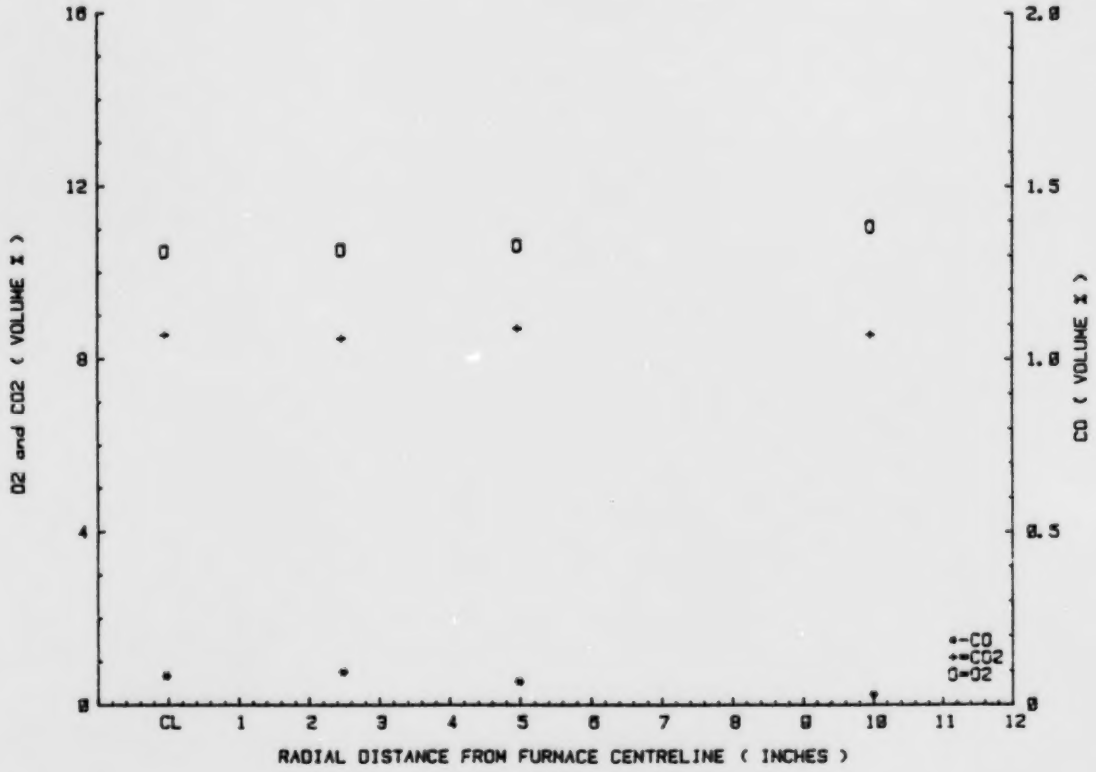


Figure 35 AIII: 25 Wt % Coal (minus 10 mesh) in No 6P Oil
(6 lb/min Injection Rate)

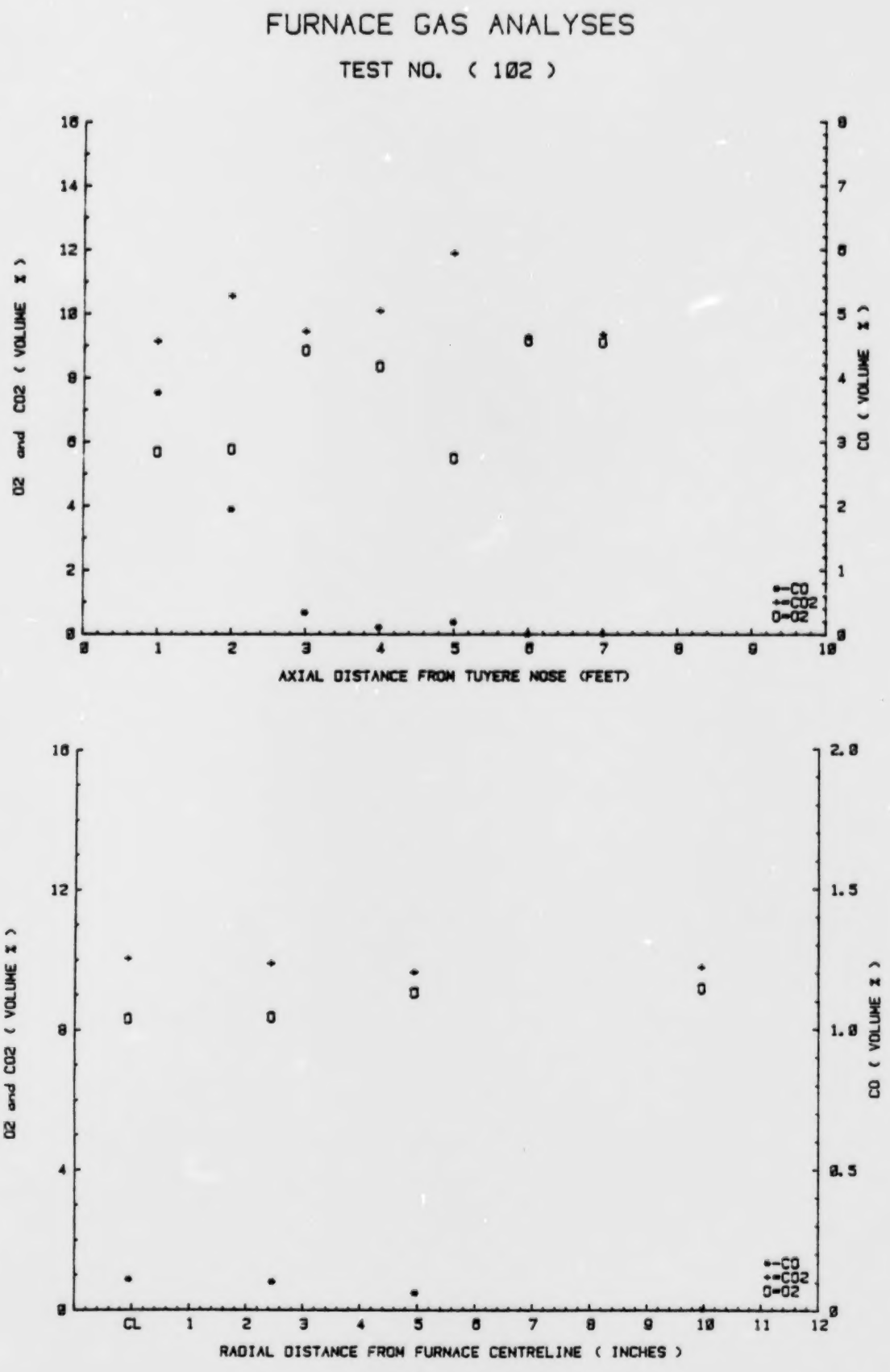


Figure 36 AIII: 50 Wt % Coal (minus 10 mesh) in No 6P Oil
(4.5 lb/min Injection Rate)

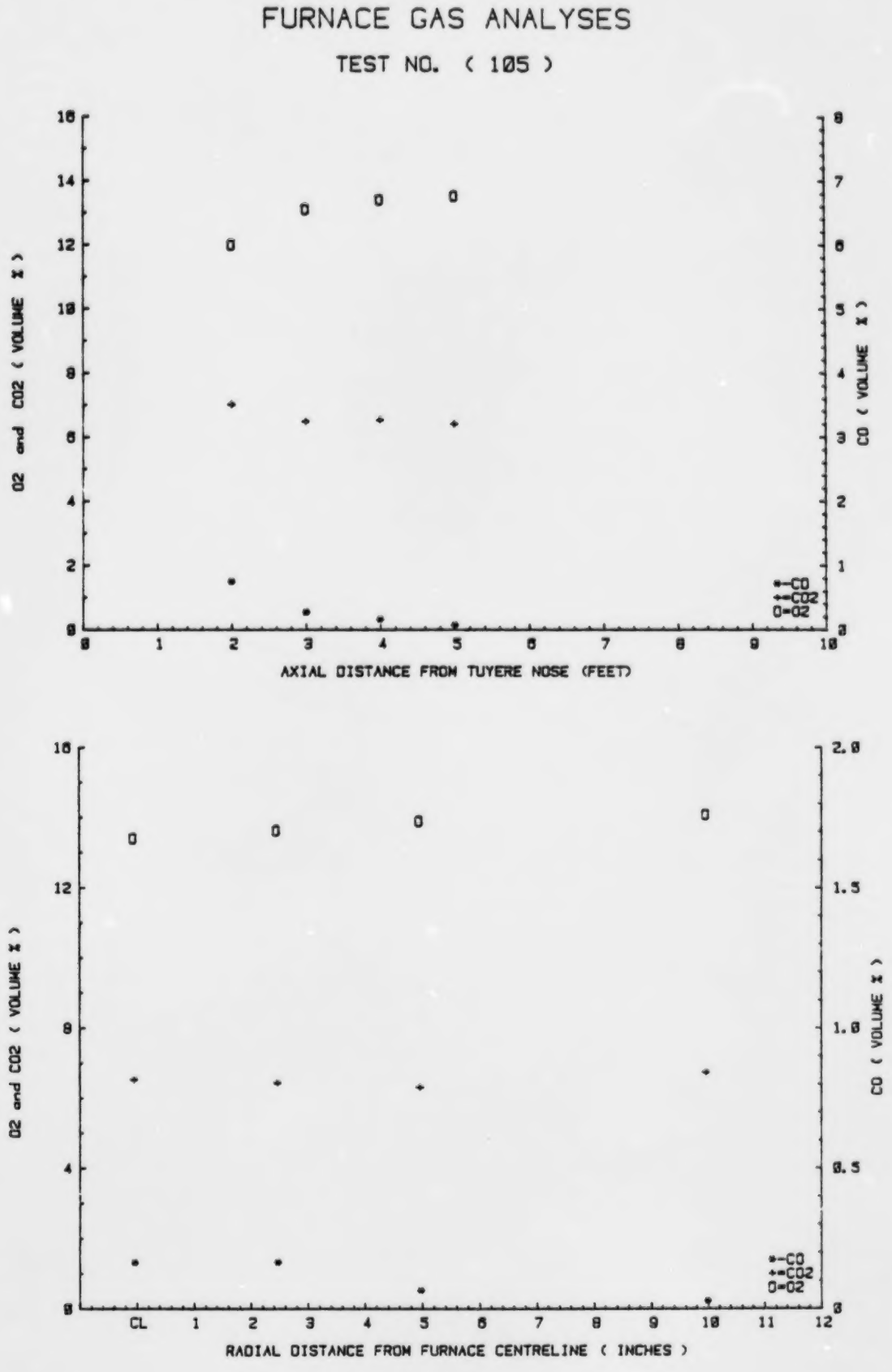

FURNACE GAS ANALYSES
TEST NO. (105)
O2 and CO2 (VOLUME %)
CO (VOLUME %)
AXIAL DISTANCE FROM TUYERE NOSE (FEET)
*-CO
+-CO2
O-O2
RADIAL DISTANCE FROM FURNACE CENTRELINE (INCHES)

Figure 37 AIII: 50 Wt % Coal (minus 10 mesh) in No 6P Oil
(4.5 lb/min Injection Rate)

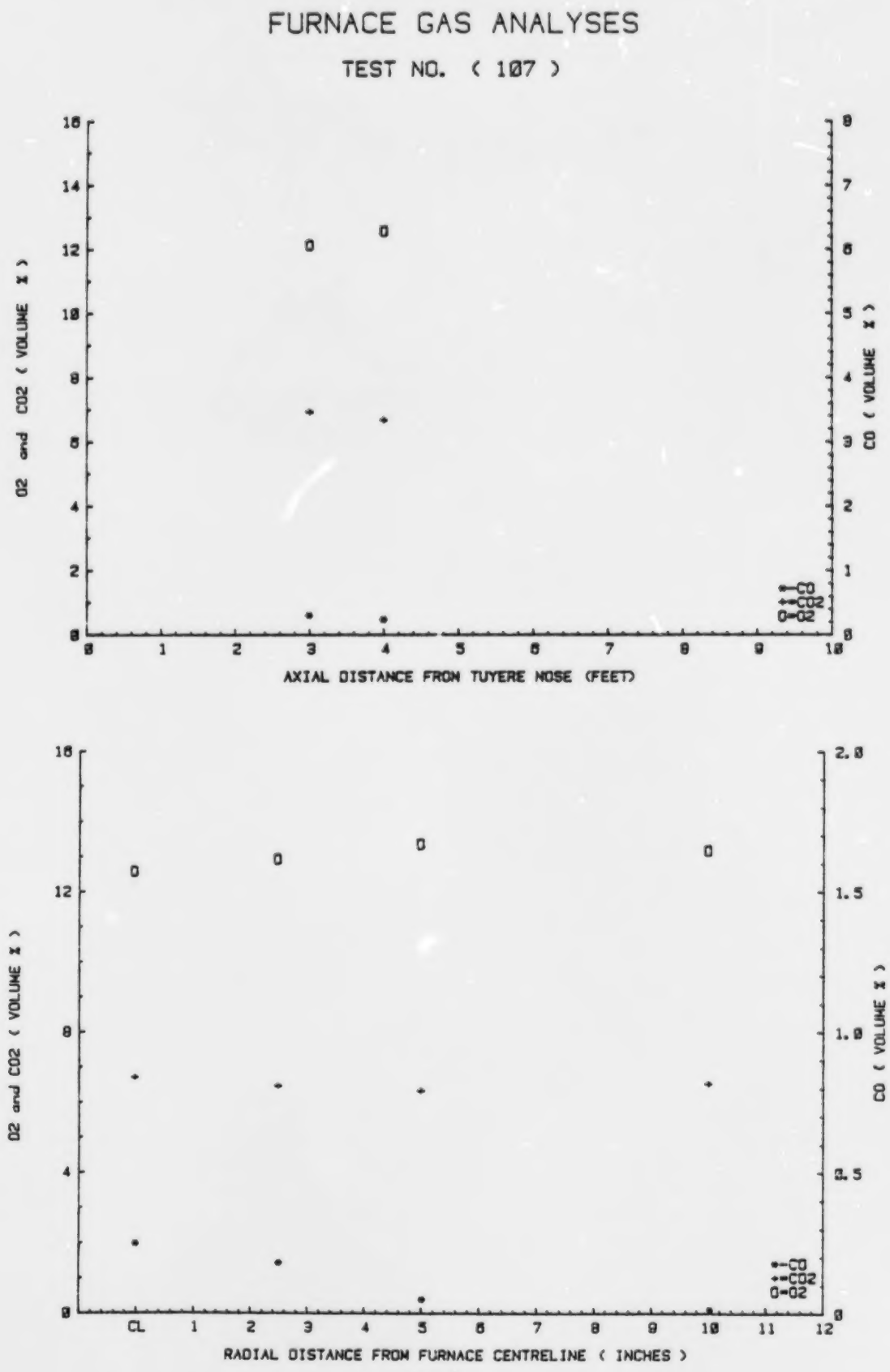

FURNACE GAS ANALYSES
TEST NO. (107)
O2 and CO2 (VOLUME %)
CO (VOLUME %)
AXIAL DISTANCE FROM TUYERE NOSE (FEET)
O-O2
+-CO2
*-CO
RADIAL DISTANCE FROM FURNACE CENTRELINE (INCHES)

Figure 38 AIII: 50 Wt % Coal (minus 10 mesh) in No 6P Oil
(6 lb/min Injection Rate)

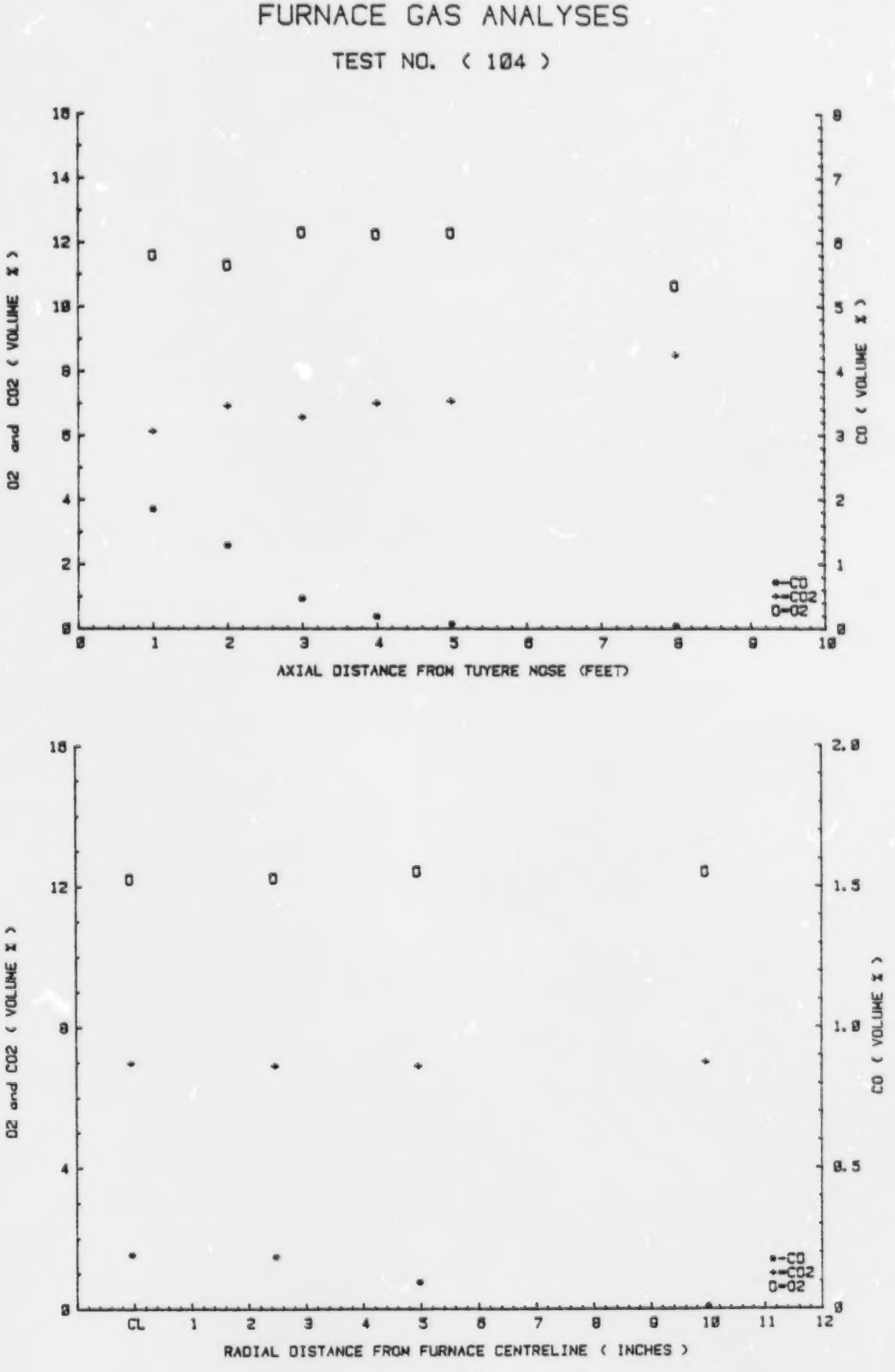


Figure 39 AIII: 50 Wt % Coal (minus 10 mesh) in No 6P Oil
(6 lb/min Injection Rate)

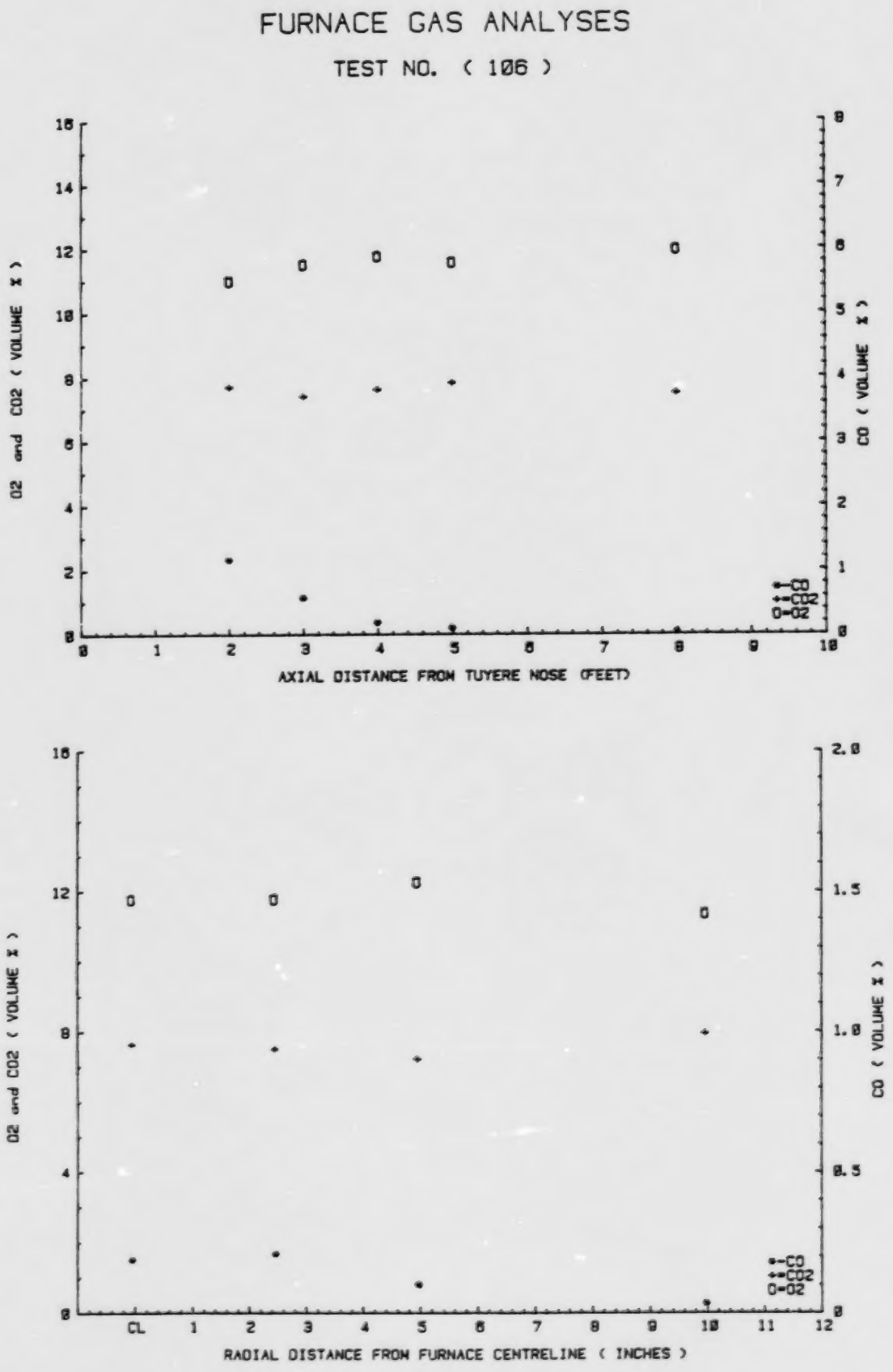

FURNACE GAS ANALYSES
TEST NO. (106)
O2 and CO2 (VOLUME %)
CO (VOLUME %)
AXIAL DISTANCE FROM TUYERE NOSE (FEET)
CO
CO2
O2
RADIAL DISTANCE FROM FURNACE CENTRELINE (INCHES)

Figure 40 AIII: Tar (4.5 lb/min Injection Rate)

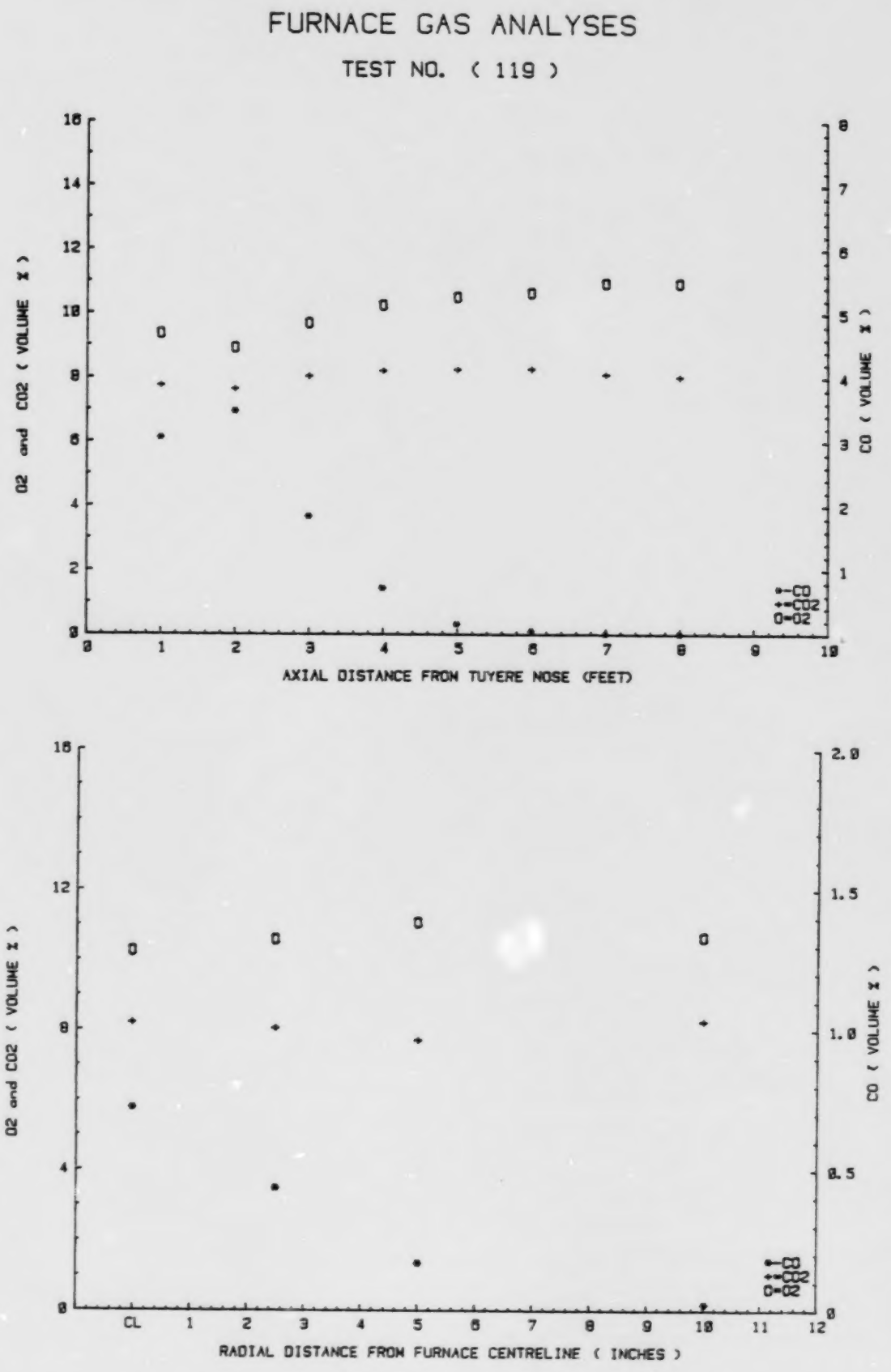

FURNACE GAS ANALYSES
TEST NO. (119)
O2 and CO2 (VOLUME %)
CO (VOLUME %)
AXIAL DISTANCE FROM TUYERE NOSE (FEET)
CO
CO2
O2
RADIAL DISTANCE FROM FURNACE CENTRELINE (INCHES)

Figure 41 AIII: Tar (4.5 lb/min Injection Rate)

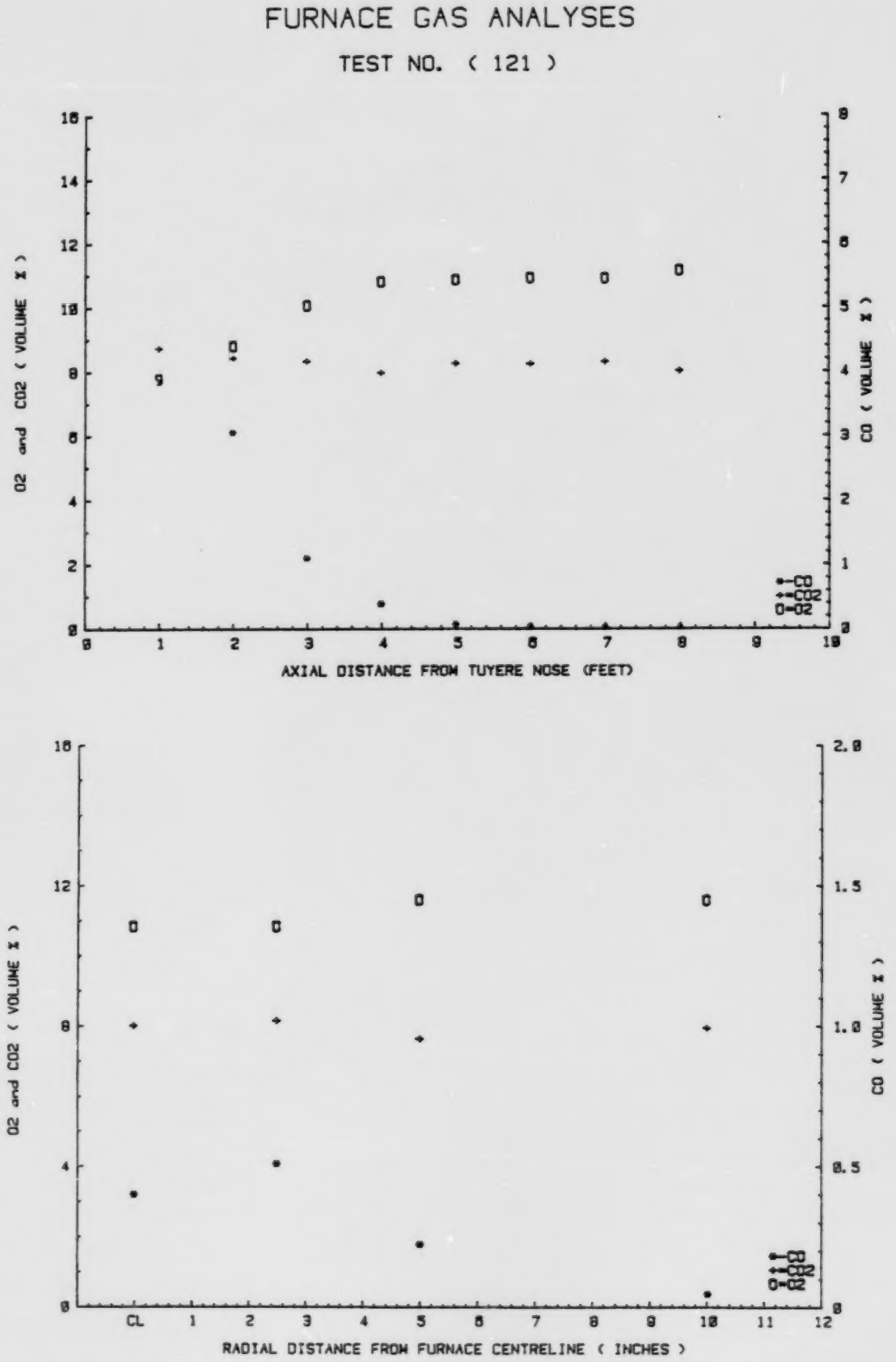

FURNACE GAS ANALYSES
TEST NO. (121)
O2 and CO2 (VOLUME %)
CO (VOLUME %)
AXIAL DISTANCE FROM TUYERE NOSE (FEET)
CO
CO2
O2
RADIAL DISTANCE FROM FURNACE CENTRELINE (INCHES)

Figure 42 AIII: Tar (6 lb/min Injection Rate)

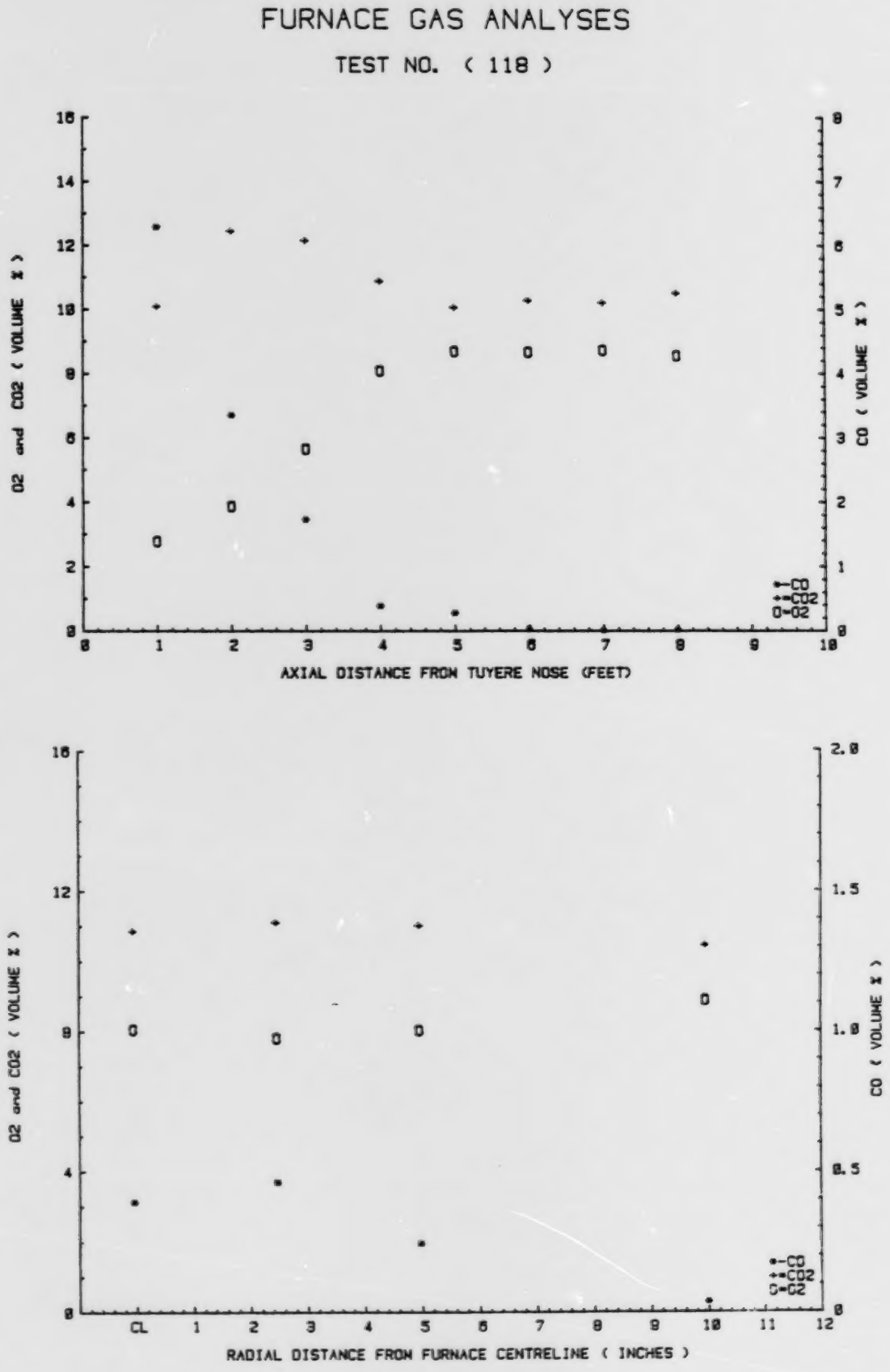

FURNACE GAS ANALYSES
TEST NO. (118)
O2 and CO2 (VOLUME %)
CO (VOLUME %)
AXIAL DISTANCE FROM TUYERE NOSE (FEET)
*-CO
+-CO2
O-O2
RADIAL DISTANCE FROM FURNACE CENTRELINE (INCHES)

Figure 43 AIII: Tar (6 lb/min Injection Rate)

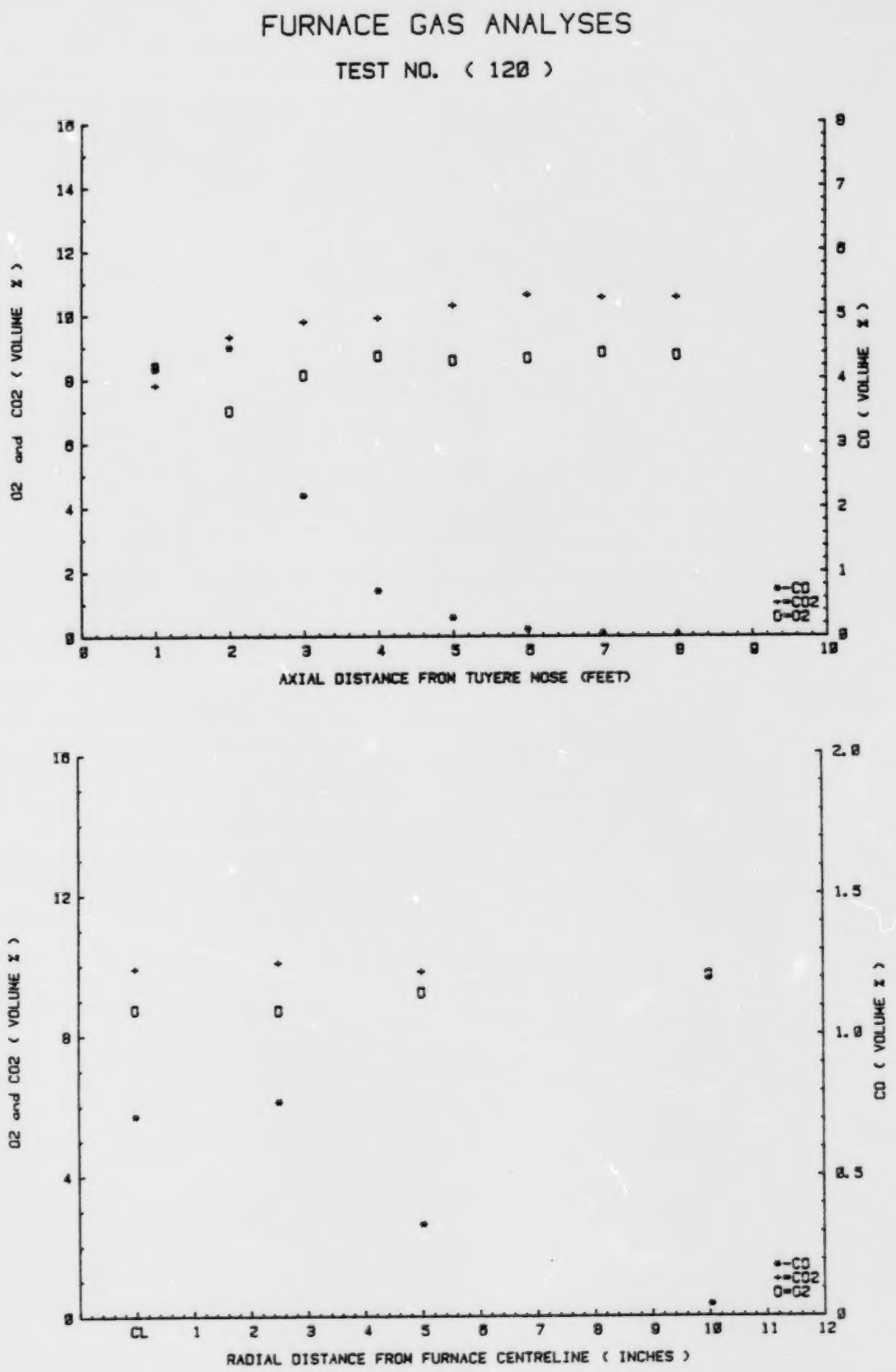

FURNACE GAS ANALYSES
TEST NO. (120)
O2 and CO2 (VOLUME %)
CO (VOLUME %)
AXIAL DISTANCE FROM TUYERE NOSE (FEET)
*-CO
+-CO2
O-O2
RADIAL DISTANCE FROM FURNACE CENTRELINE (INCHES)

Figure 44 AIII: 25 Wt % Coal (minus 100 mesh) in Tar (4.5 lb/min Injection Rate)

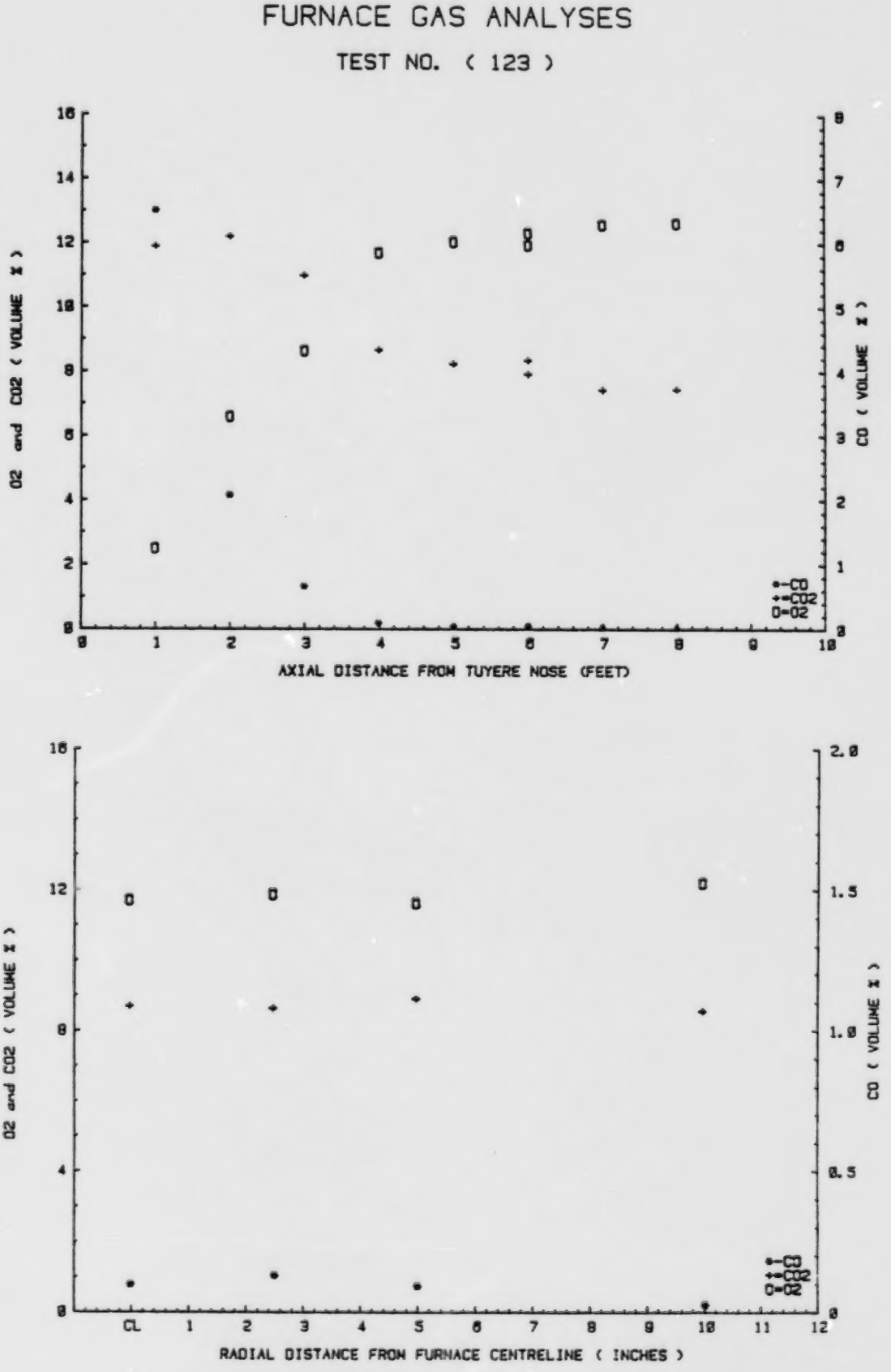

FURNACE GAS ANALYSES
TEST NO. (123)
O2 and CO2 (VOLUME %)
CO (VOLUME %)
AXIAL DISTANCE FROM TUYERE NOSE (FEET)
CO
CO2
O2
RADIAL DISTANCE FROM FURNACE CENTRELINE (INCHES)

Figure 45 AIII: 25 Wt % Coal (minus 100 mesh) in Tar (4.5 lb/min Injection Rate)

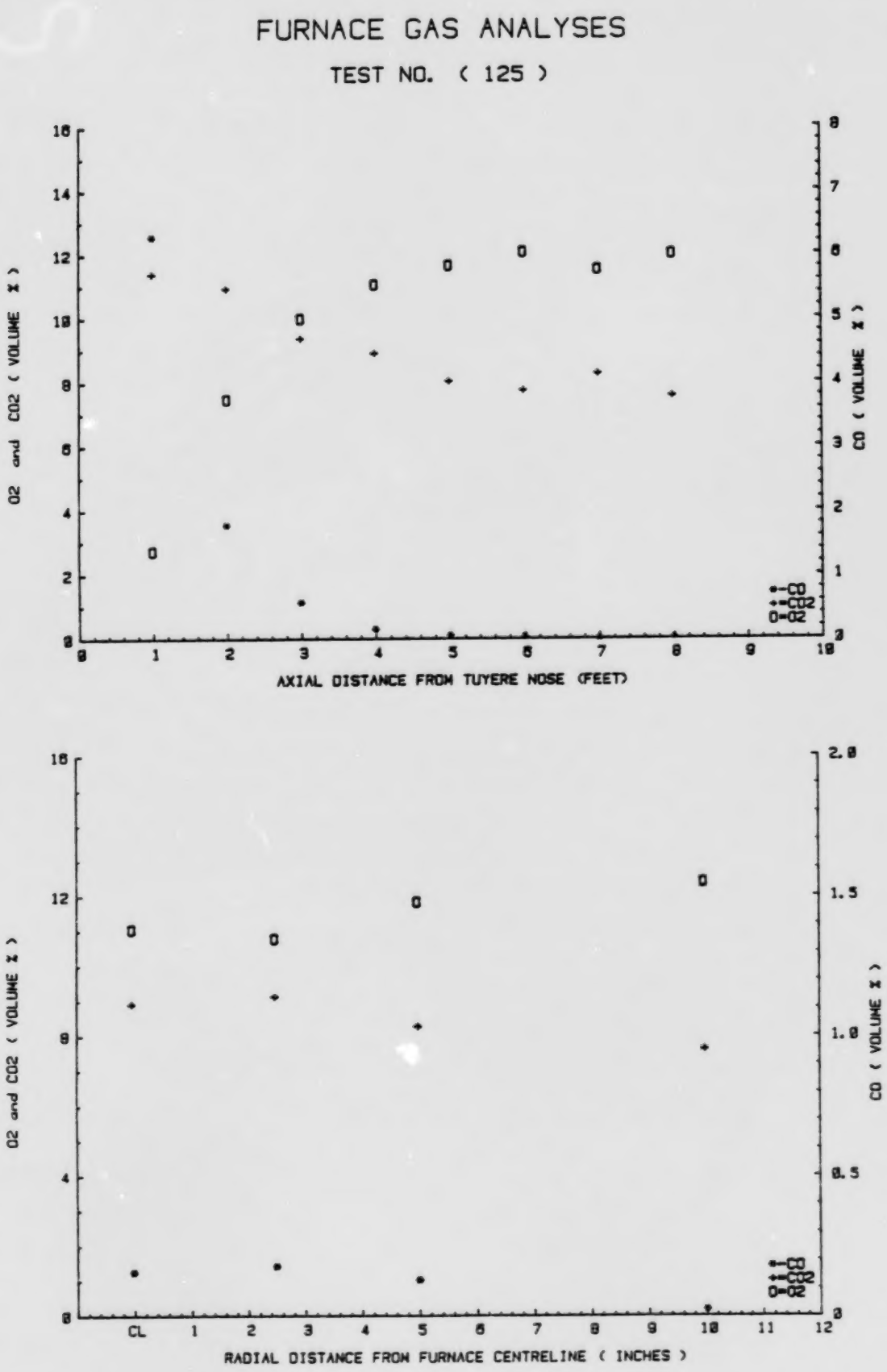


Figure 46 AIII: 25 Wt % Coal (minus 100 mesh) in Tar (6 lb/min Injection Rate)

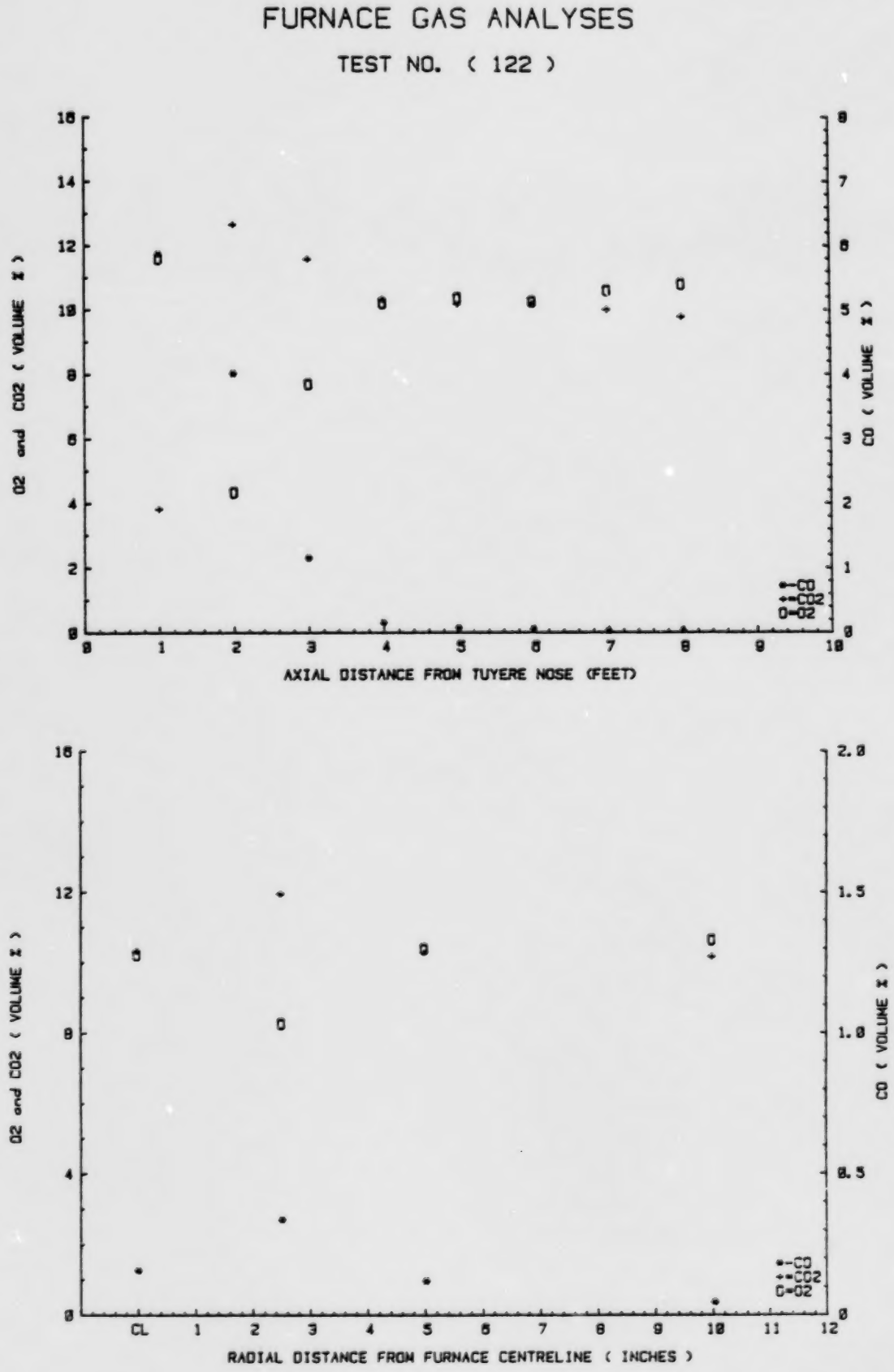


Figure 47 AIII: 25 Wt % Coal (minus 100 mesh) in Tar (6 lb/min Injection Rate)

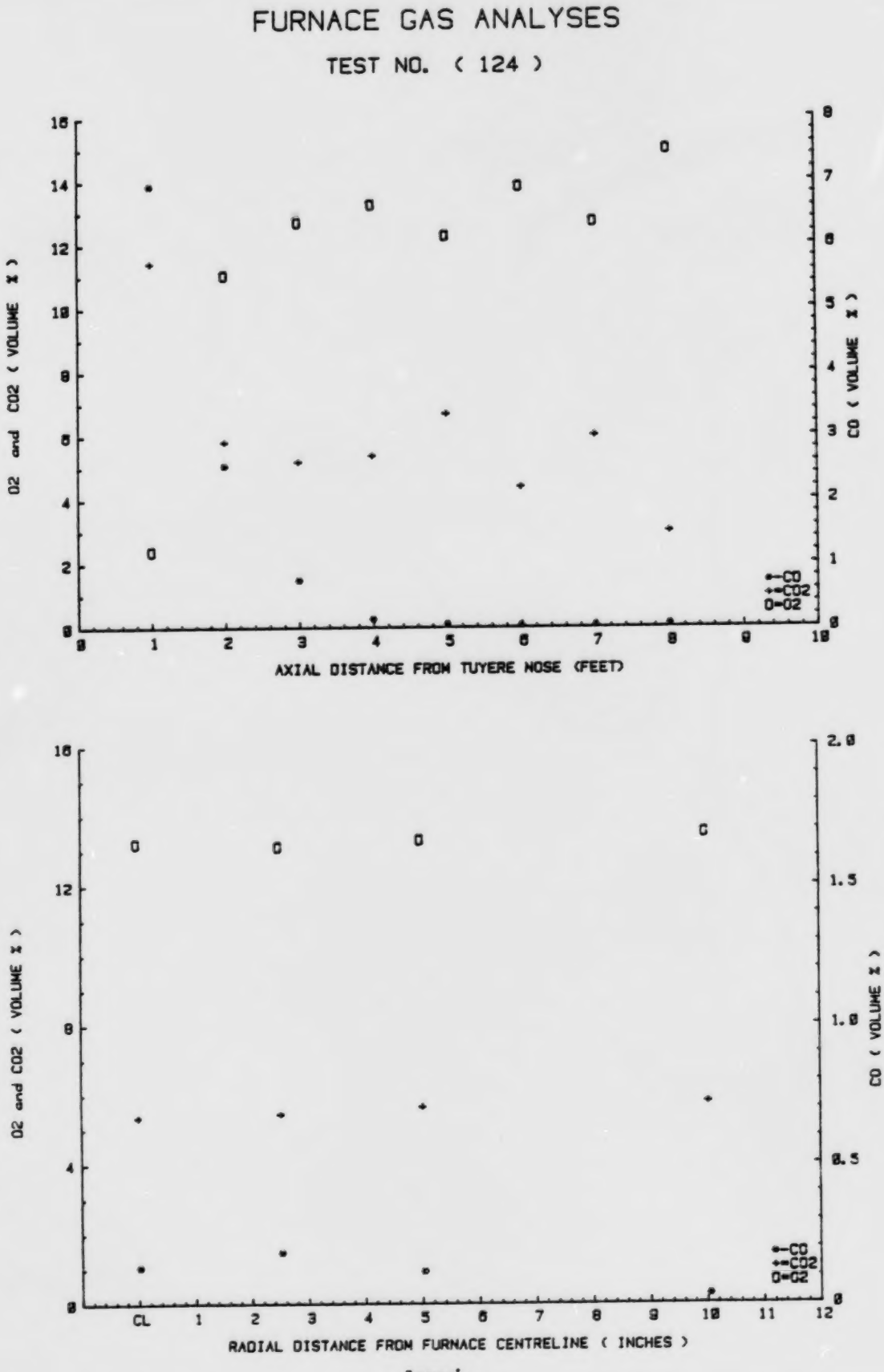


Figure 48 AIII: 50 Wt % Coal (minus 100 mesh) in Tar (4.5 lb/min Injection Rate)

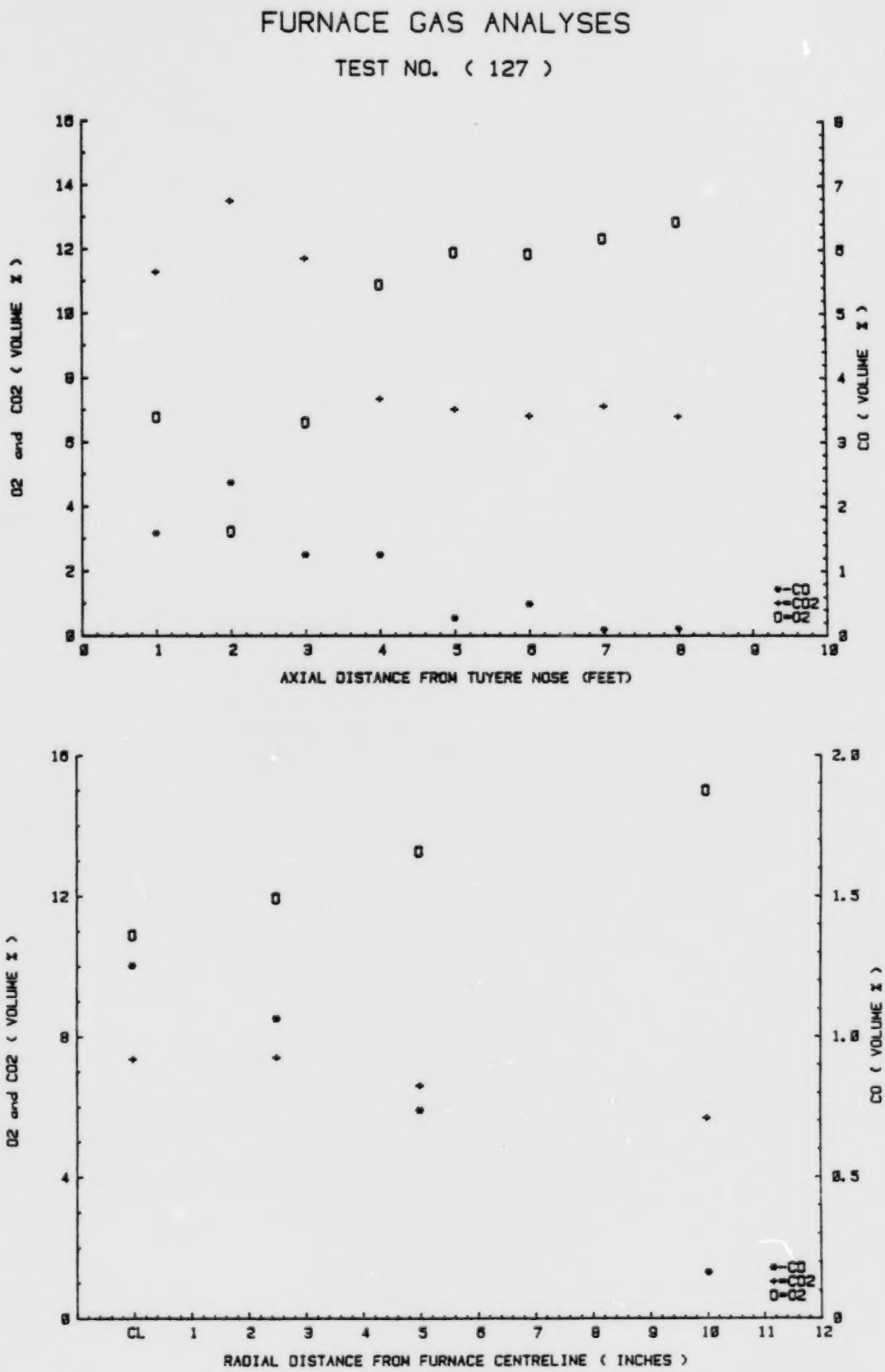


Figure 49 AIII: 50 Wt % Coal (minus 100 mesh) in Tar (4.5 lb/min Injection Rate)

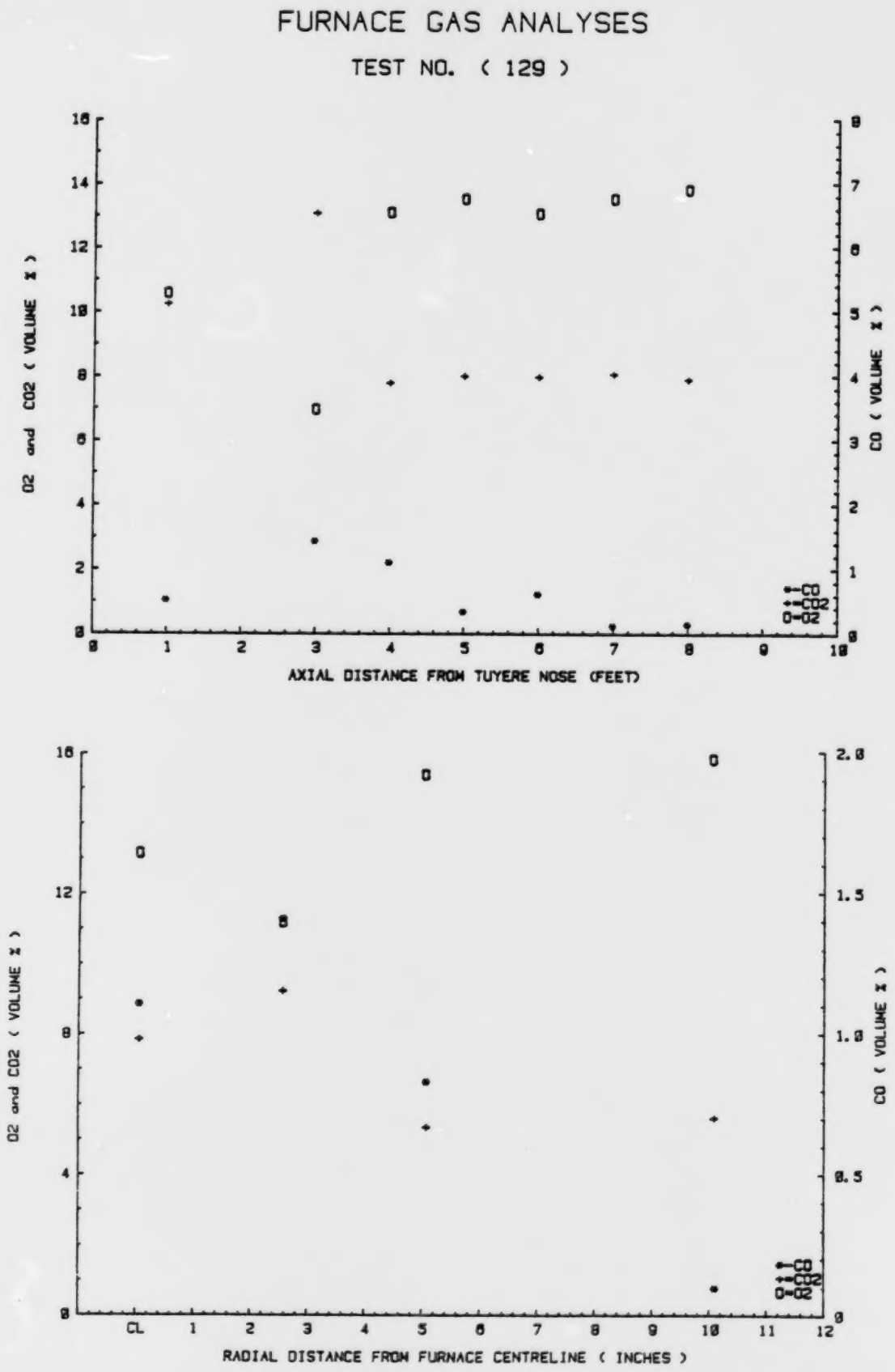


Figure 50 AIII: 50 Wt % Coal (minus 100 mesh) in Tar (6 lb/min Injection Rate)

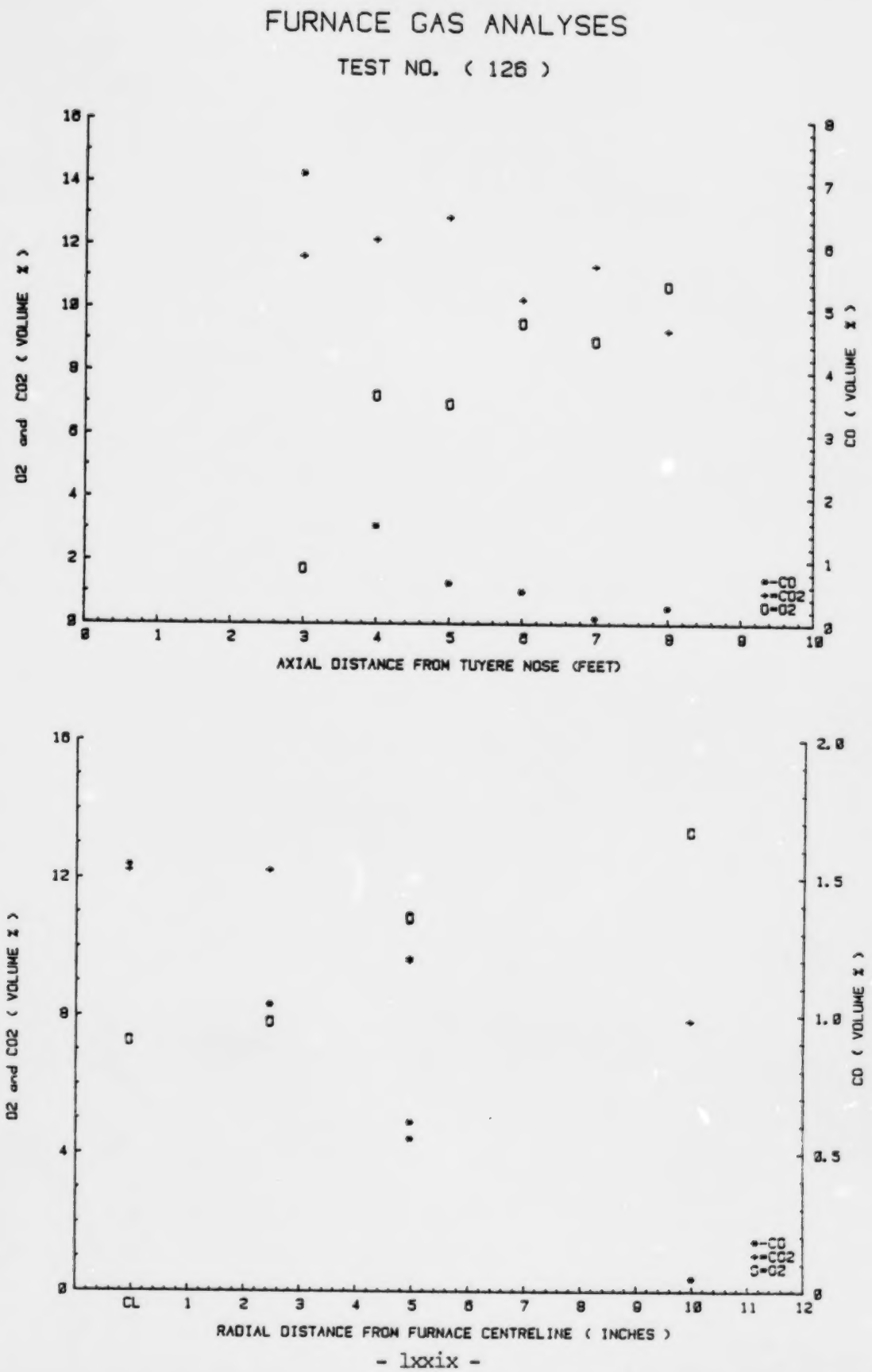


Figure 51 AIII: 50 Wt % Coal (minus 100 mesh) in Tar (6 lb/min Injection Rate)

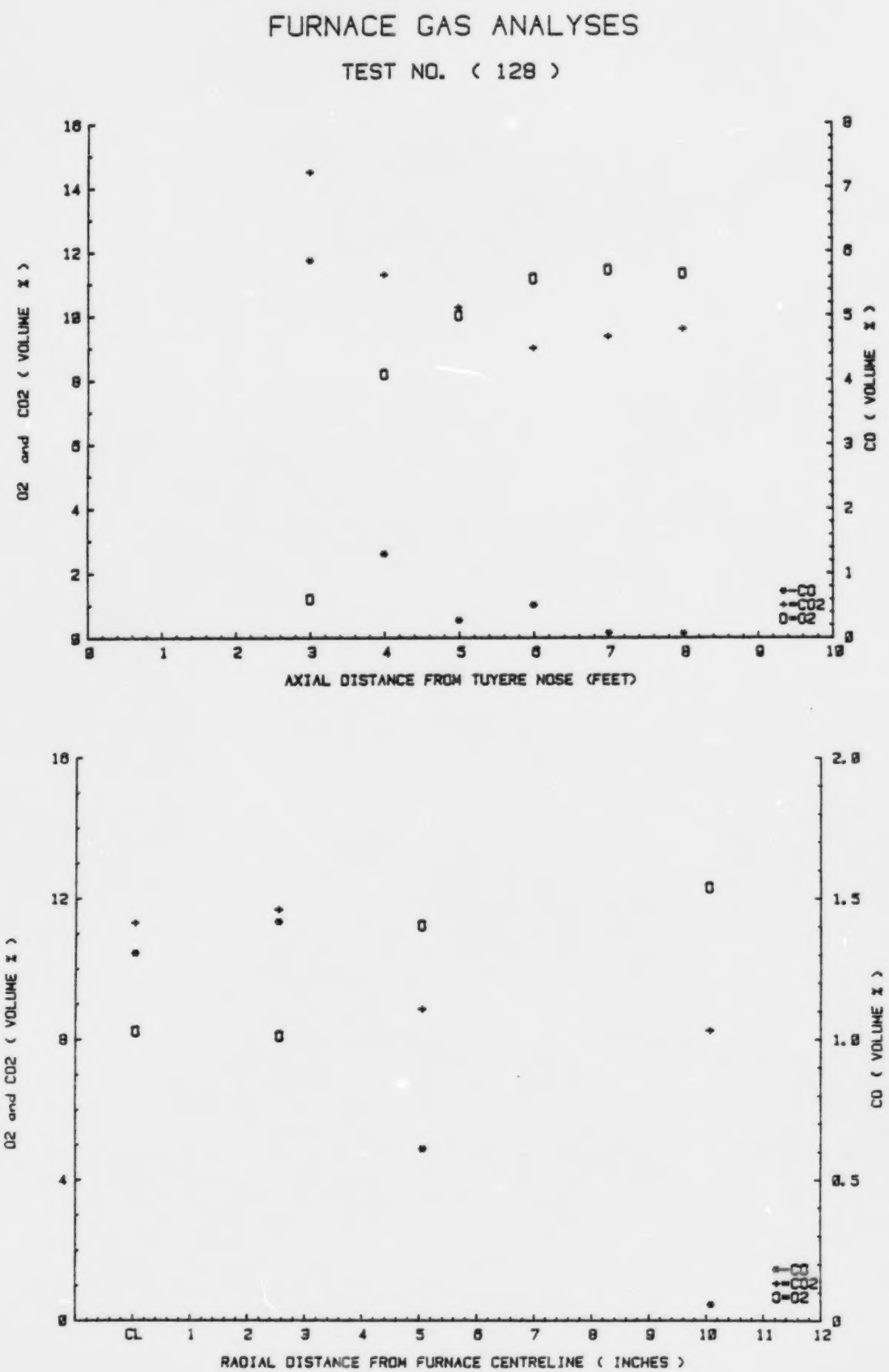

FURNACE GAS ANALYSES
TEST NO. (128)
O2 and CO2 (VOLUME %)
CO (VOLUME %)
AXIAL DISTANCE FROM TUYERE NOSE (FEET)
•=CO
+=CO2
O=O2
RADIAL DISTANCE FROM FURNACE CENTRELINE (INCHES)

Figure 52 AIII: 25 Wt % Coal (minus 35 mesh) in Tar (4.5 lb/min Injection Rate

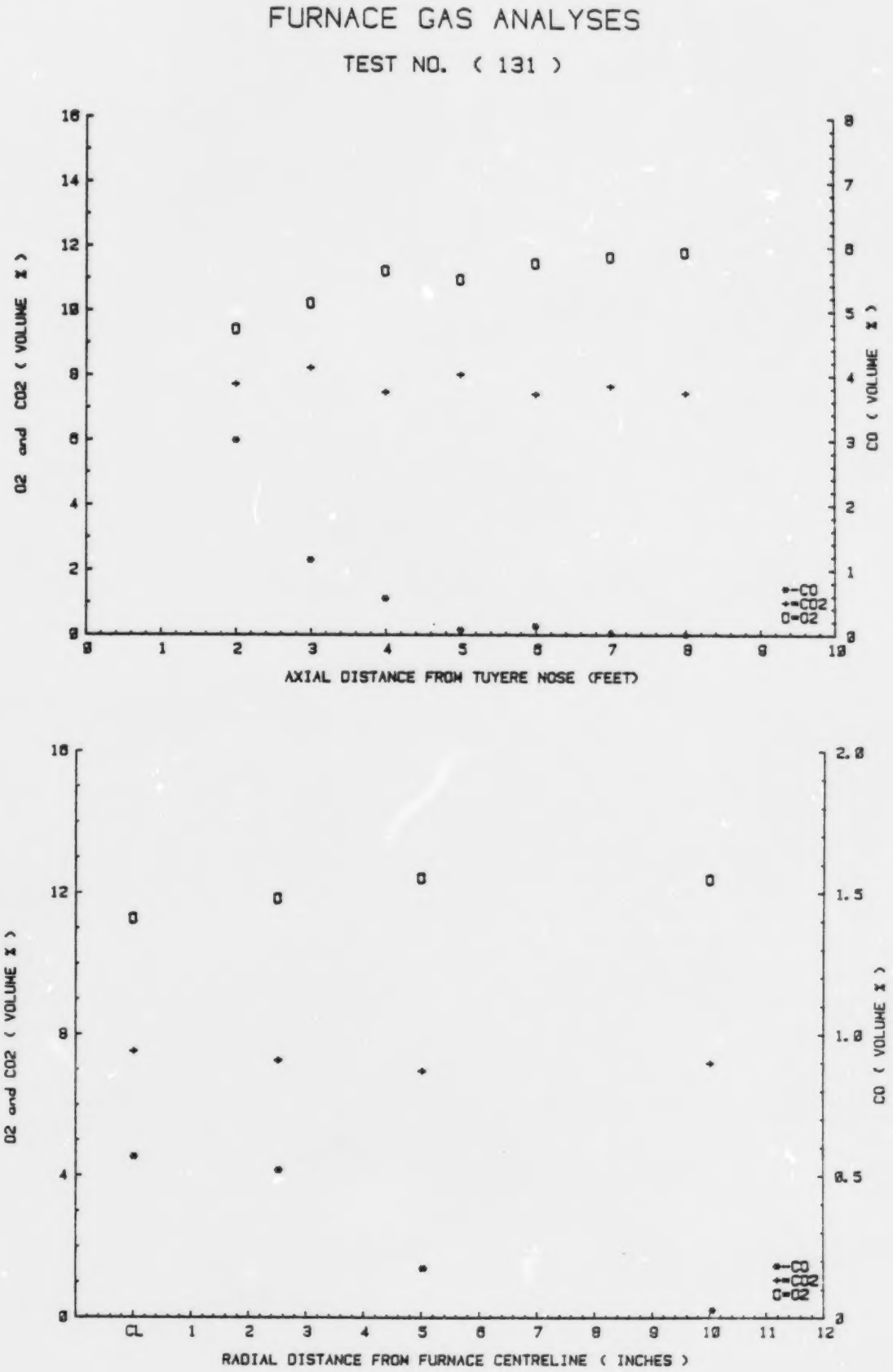


Figure 53 AIII: 25 Wt % Coal (minus 35 mesh) in Tar (4.5 lb/min Injection Rate)

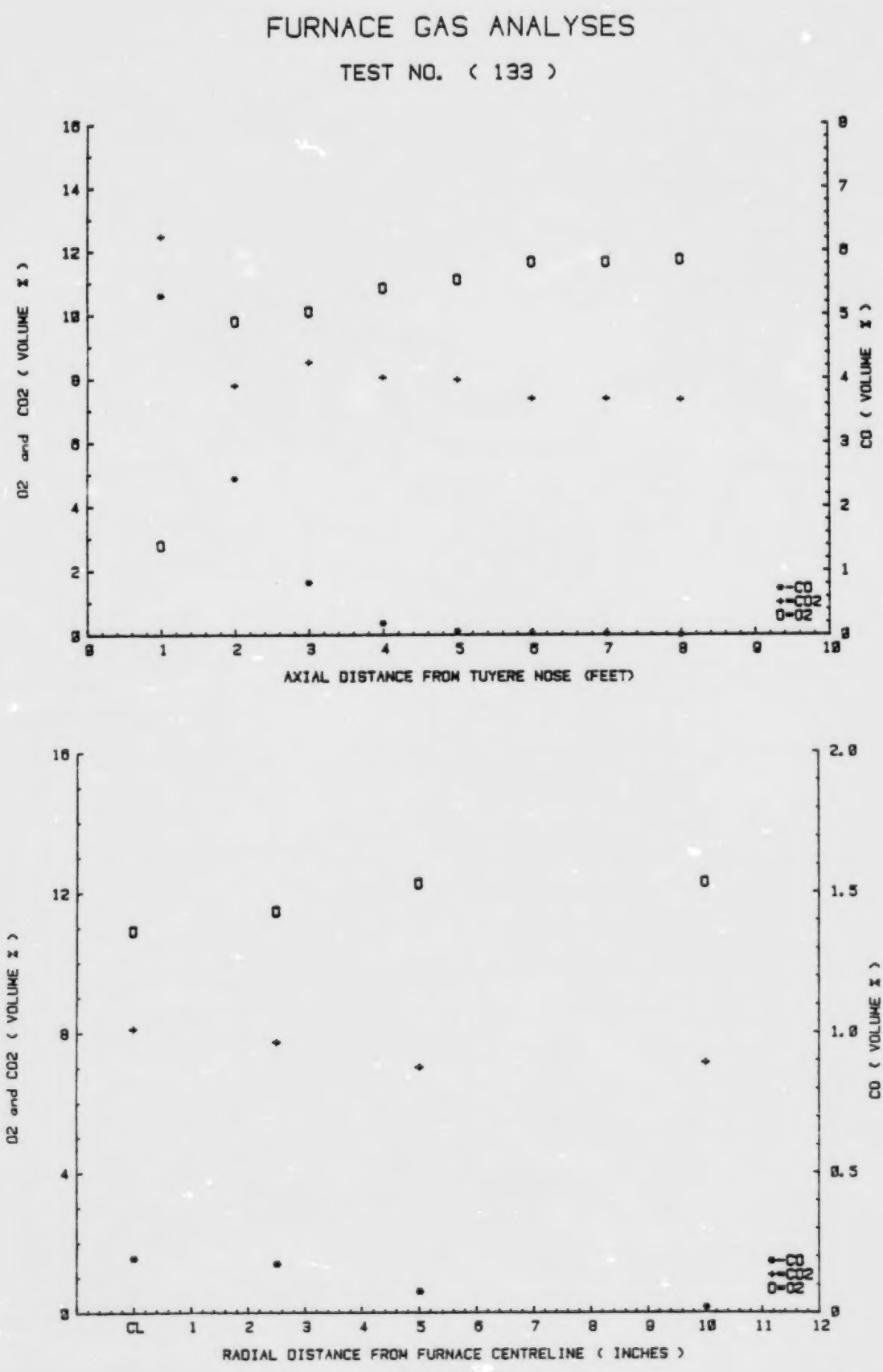
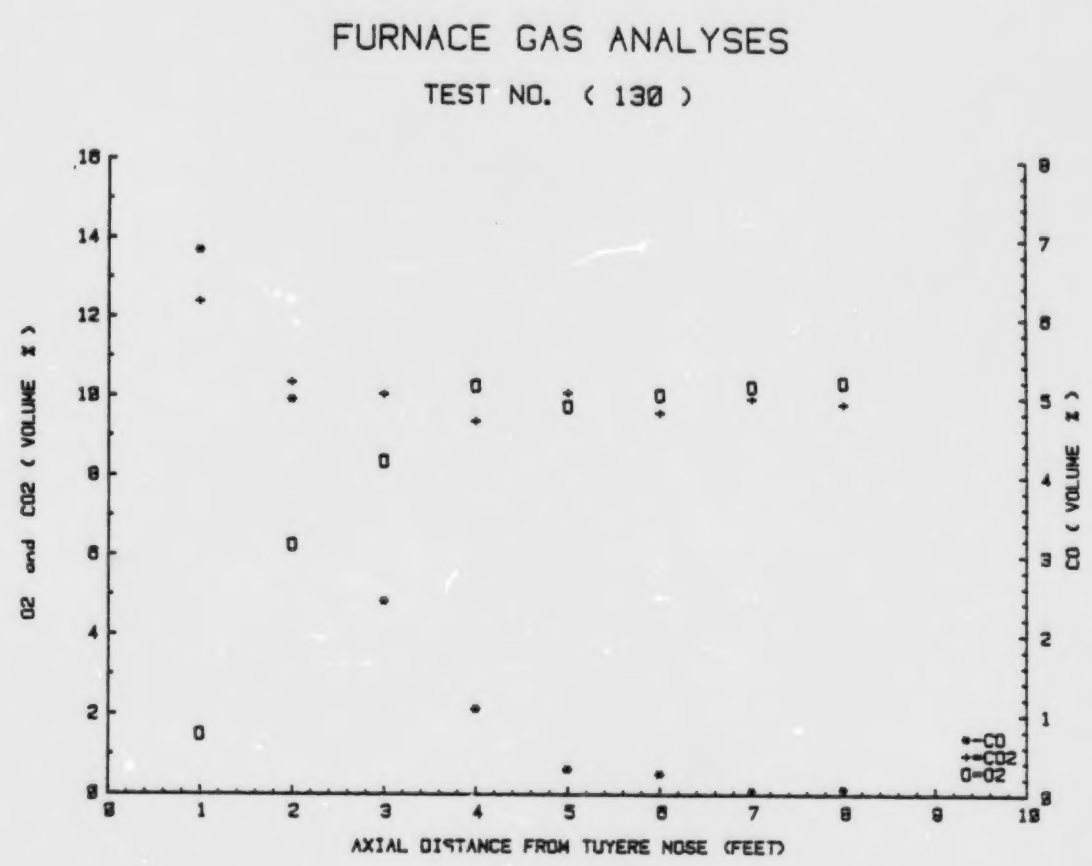


Figure 54 AIII: 25 Wt % Coal (minus 35 mesh) in Tar (6 lb/min Injection Rate)



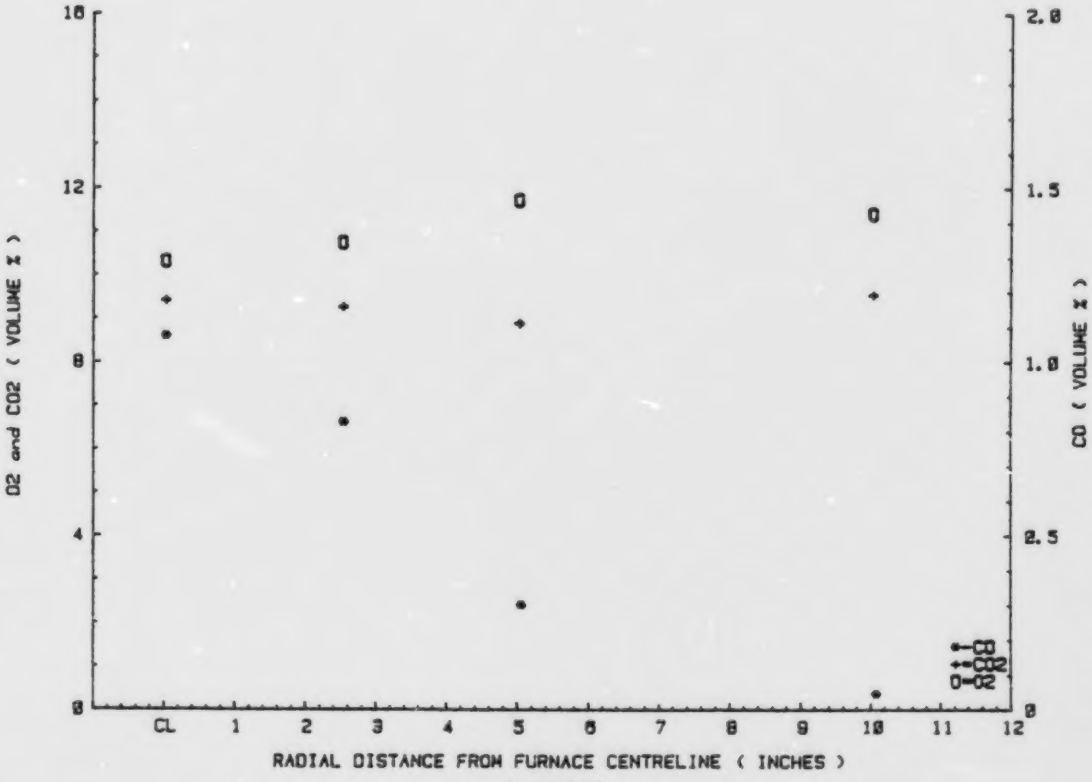


Figure 55 AIII: 25 Wt % Coal (minus 35 mesh) in Tar (6 lb/min Injection Rate)

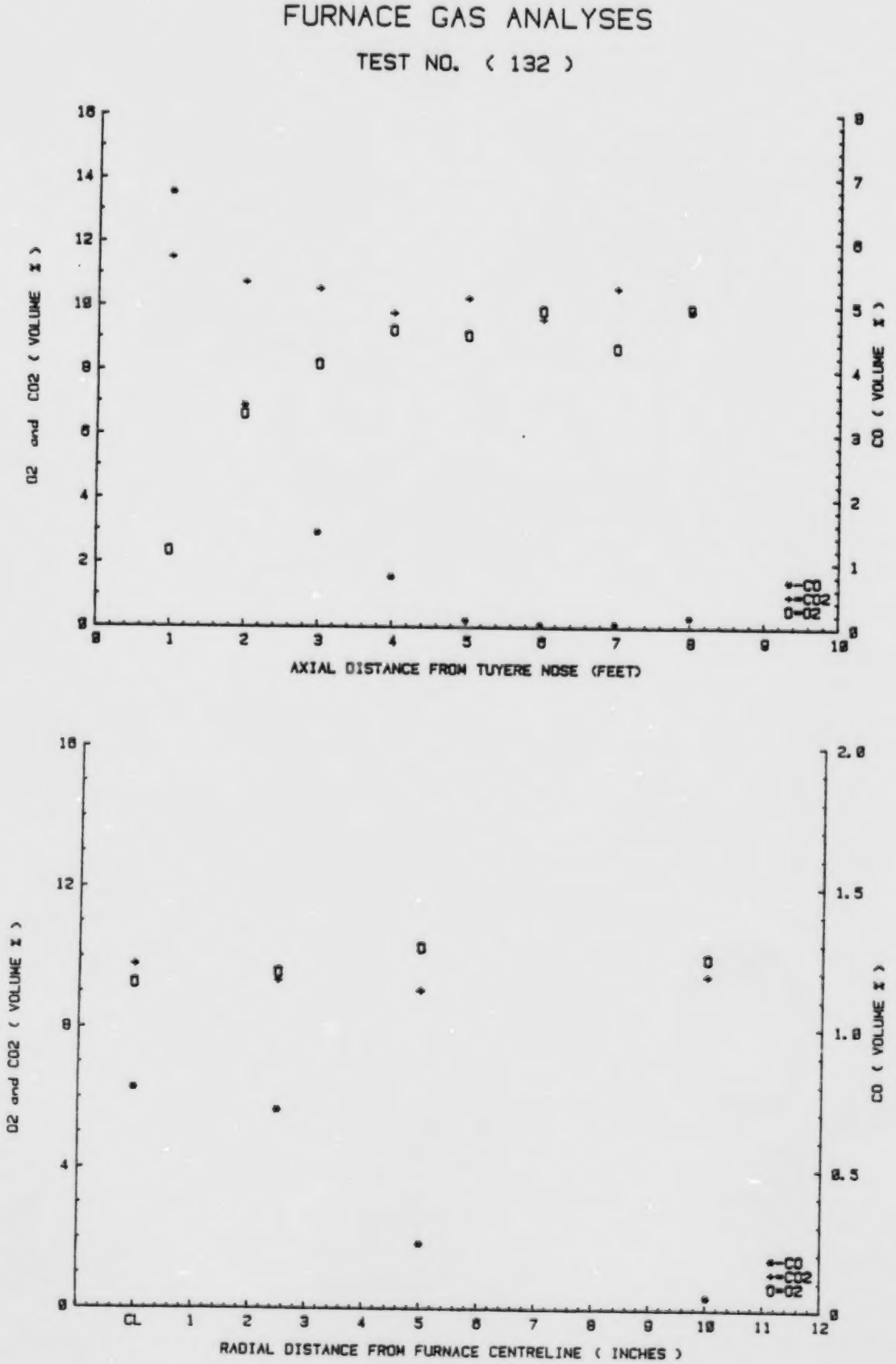


Figure 56 AIII: 50 Wt % Coal (minus 35 mesh) in Tar (4.5 lb/min Injection Rate)

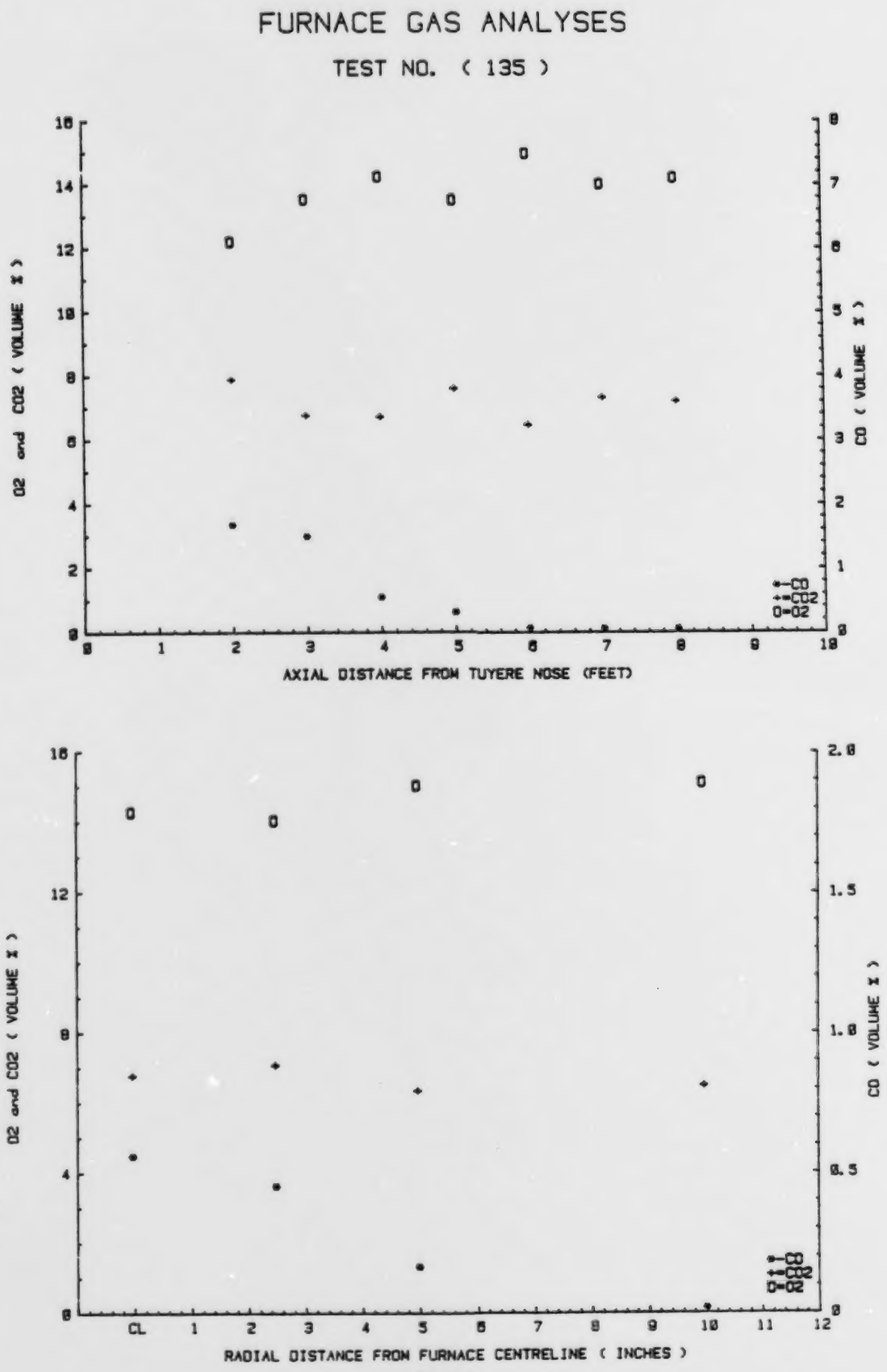


Figure 57 AIII: 50 Wt % Coal (minus 35 mesh) in Tar (4.5 lb/min Injection Rate)

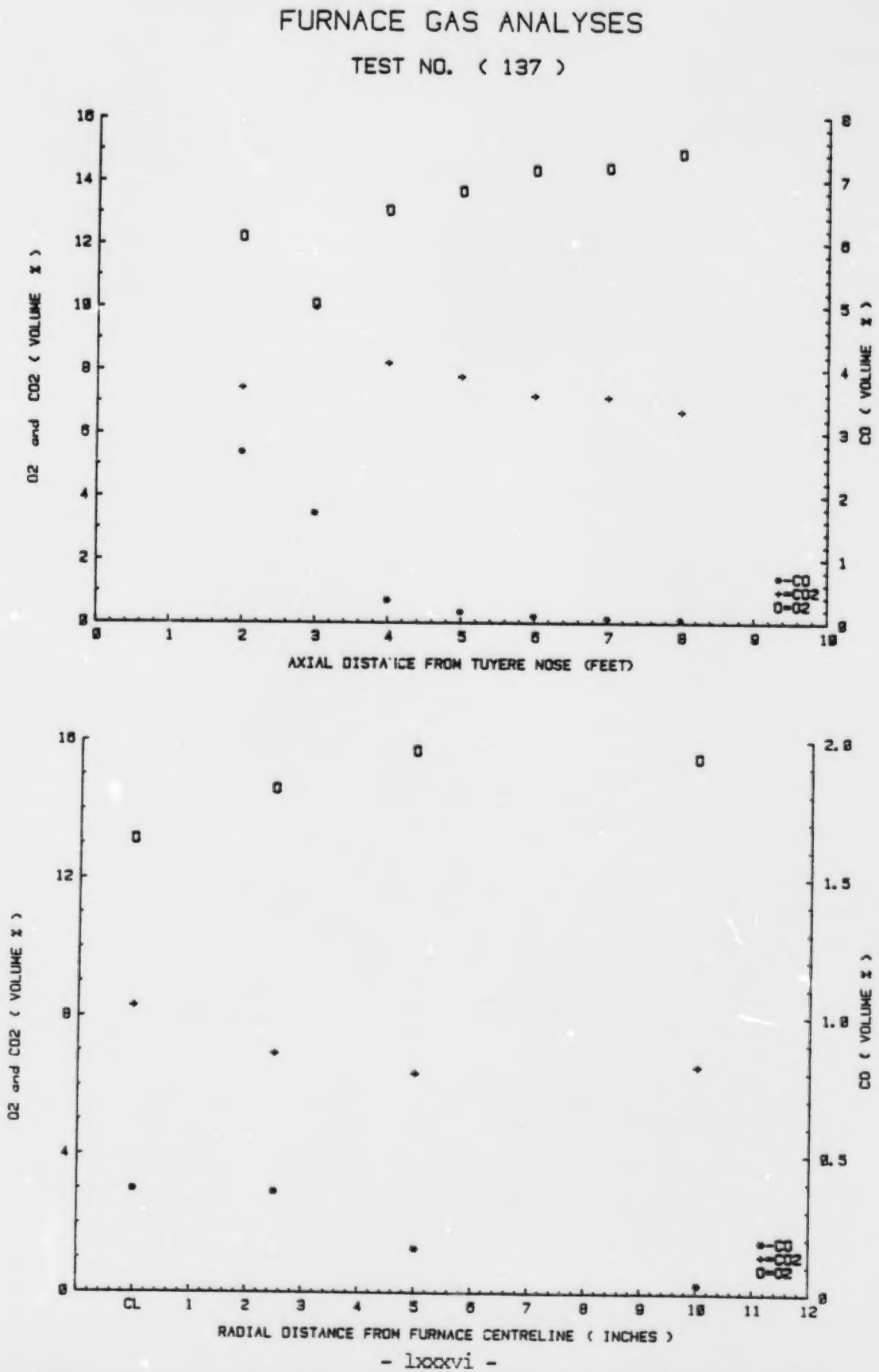

FURNACE GAS ANALYSES
TEST NO. (137)
O2 and CO2 (VOLUME %)
CO (VOLUME %)
AXIAL DISTANCE FROM TUYERE NOSE (FEET)
CO
CO2
O2
RADIAL DISTANCE FROM FURNACE CENTRELINE (INCHES)

Figure 58 AIII: 50 Wt % Coal (minus 35 mesh) in Tar (6 lb/min Injection Rate)

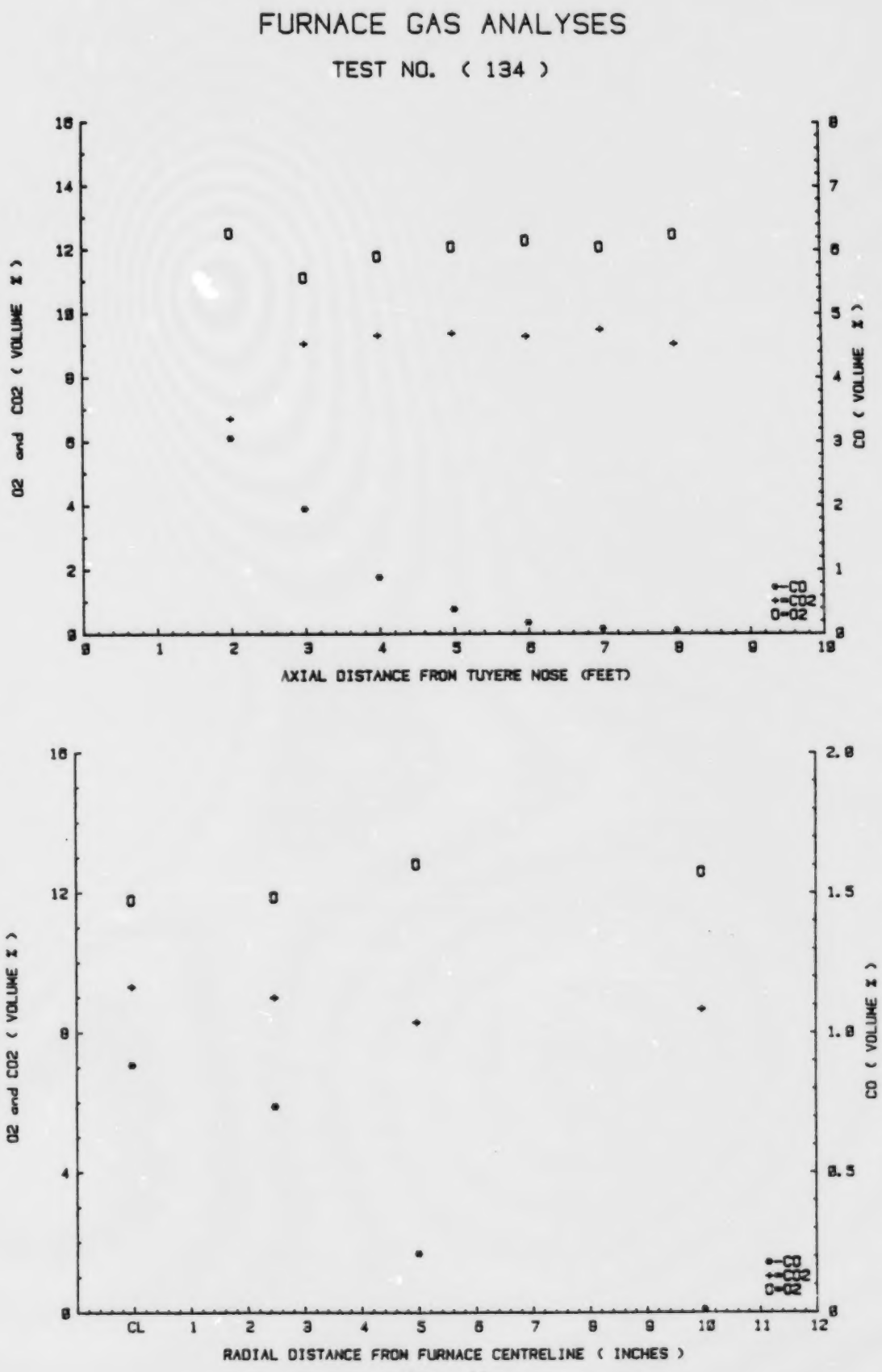


Figure 59 AIII: 50 Wt % Coal (minus 35 mesh) in Tar (6 lb/min Injection Rate)

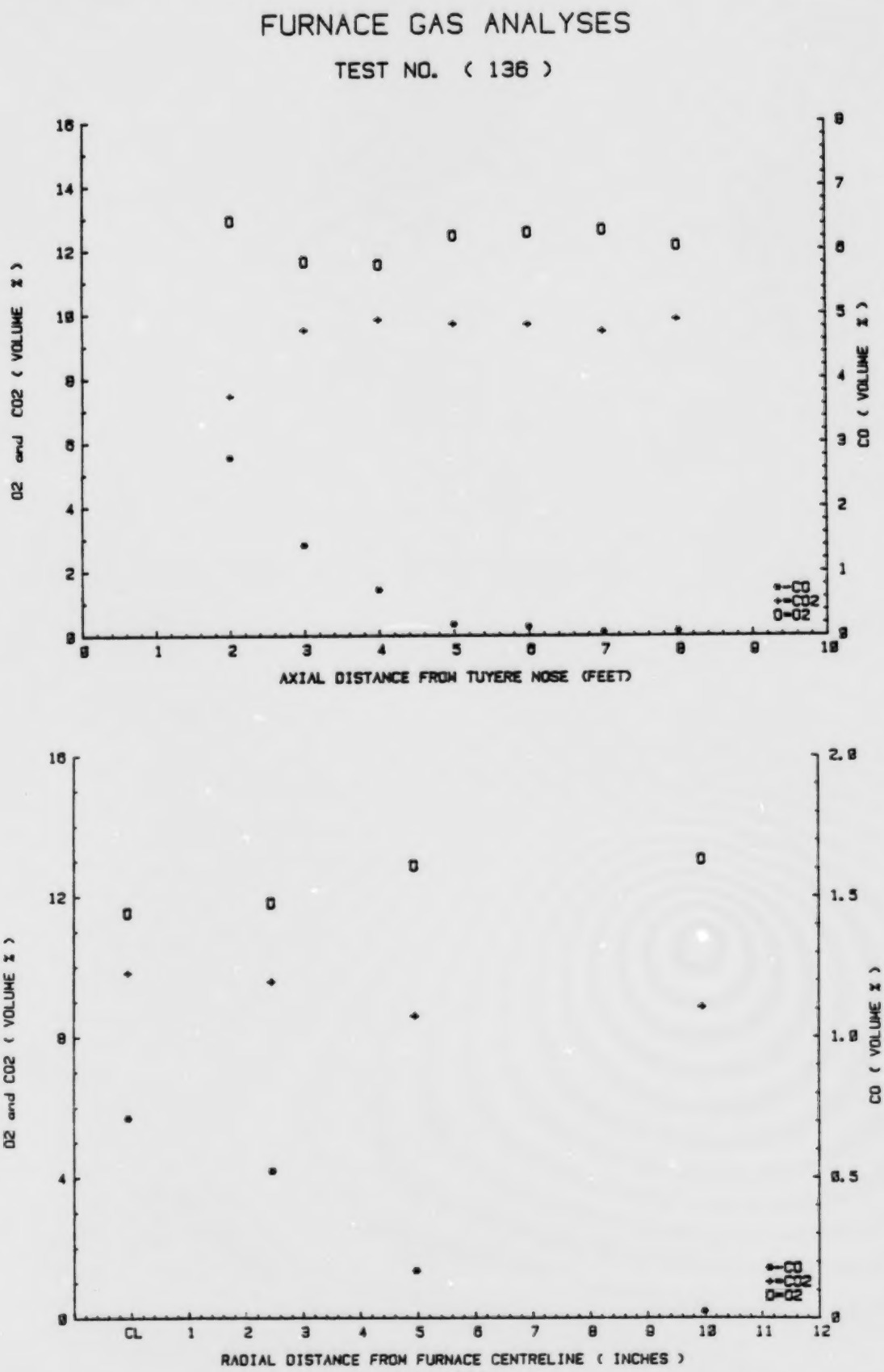


Figure 60 AIII: 25 Wt % Coal (minus 10 mesh) in Tar (4.5 lb/min Injection Rate)

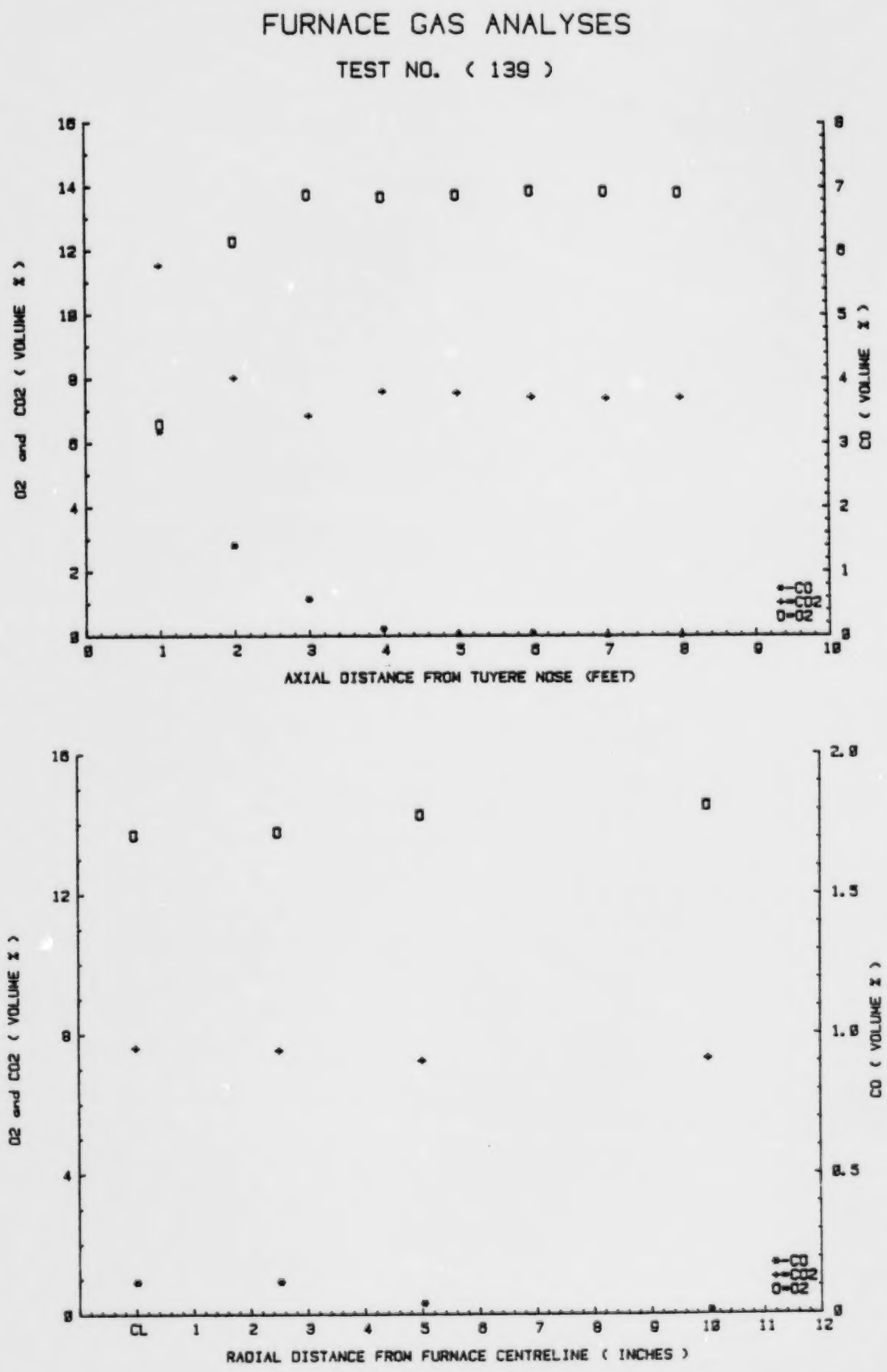
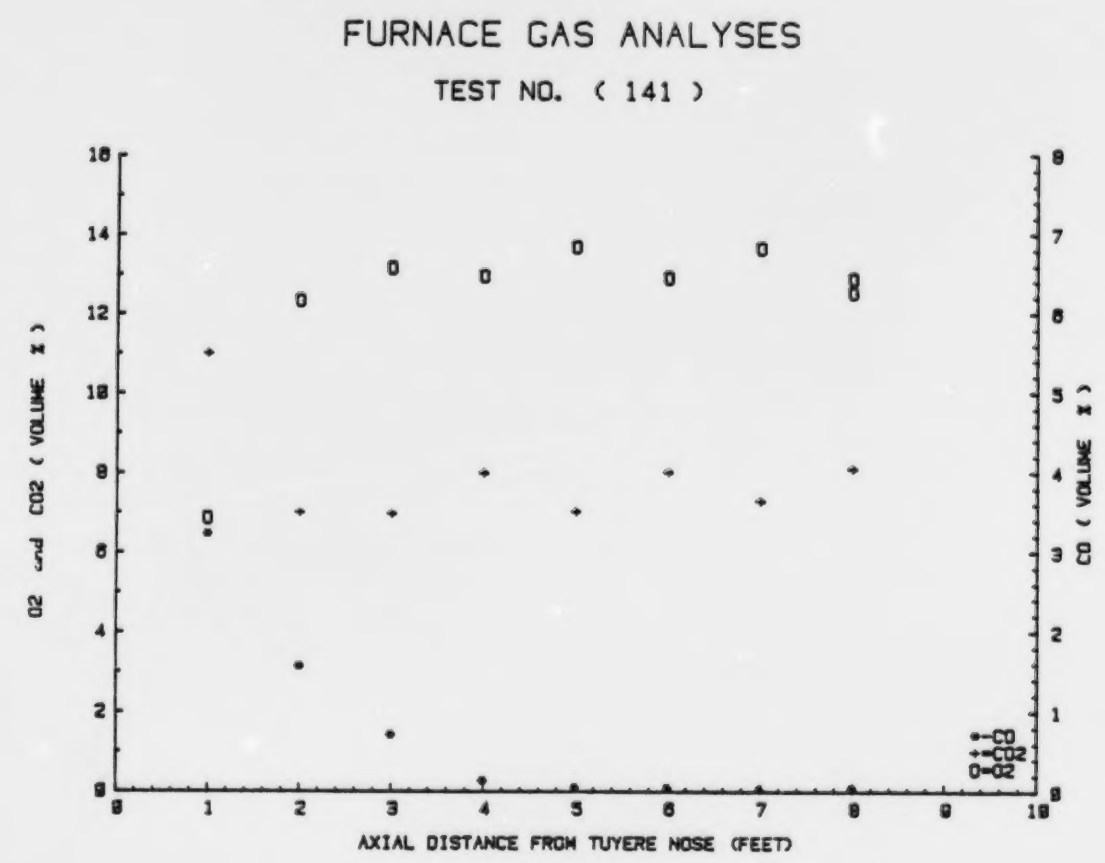

FURNACE GAS ANALYSES
TEST NO. (139)
O2 and CO2 (VOLUME %)
CO (VOLUME %)
AXIAL DISTANCE FROM TUYERE NOSE (FEET)
CO
CO2
O2
RADIAL DISTANCE FROM FURNACE CENTRELINE (INCHES)

Figure 61 AIII: 25 Wt % Coal (minus 10 mesh) in Tar (4.5 lb/min Injection Rate)



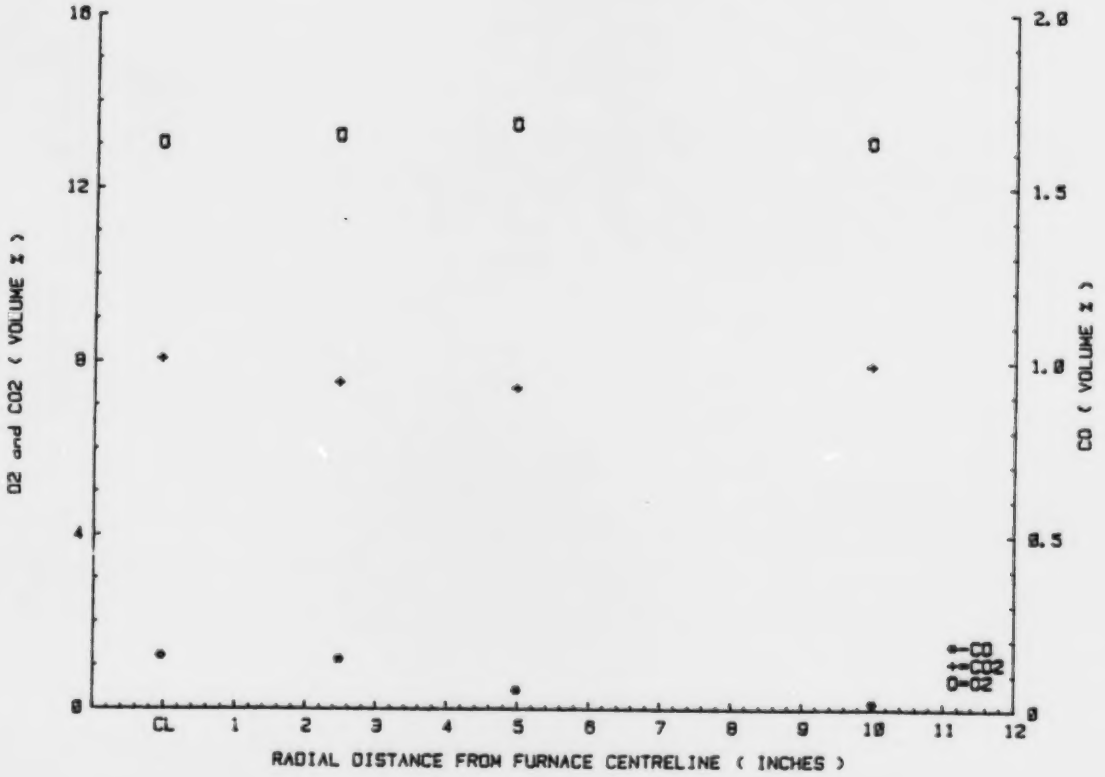
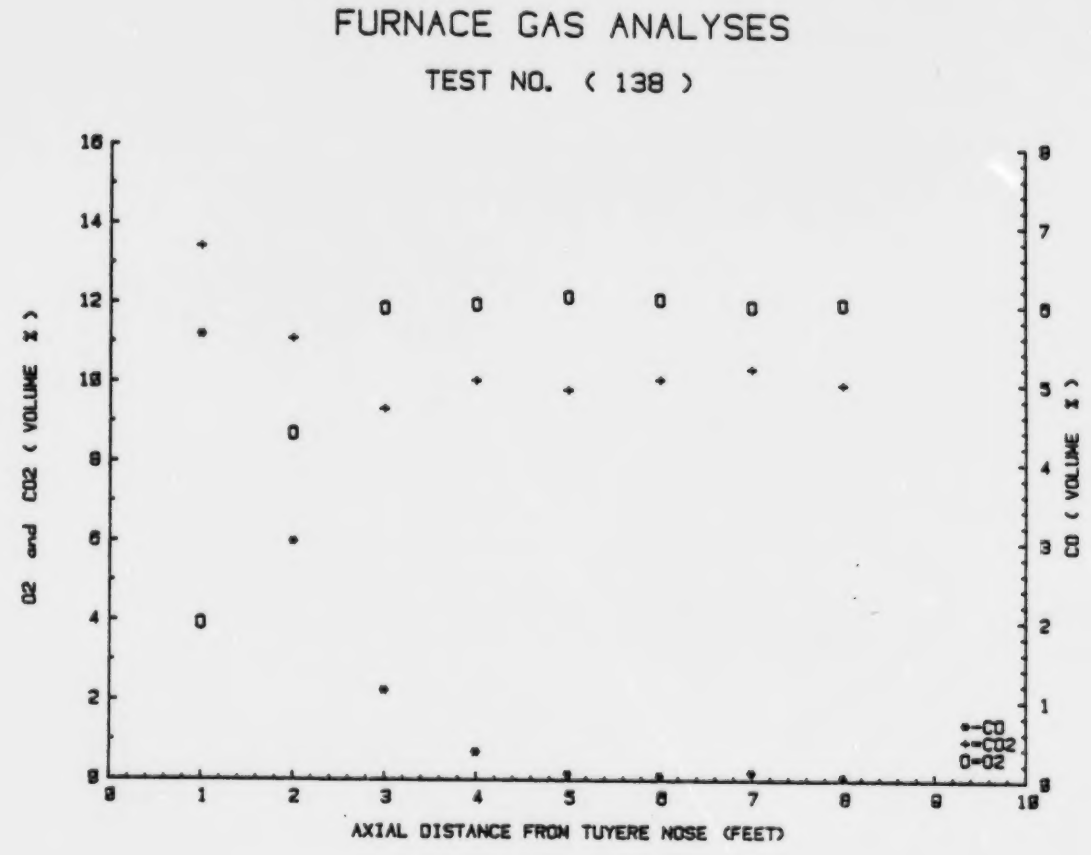


Figure 62 AIII: 25 Wt % Coal (minus 10 mesh) in Tar (6 lb/min Injection Rate)



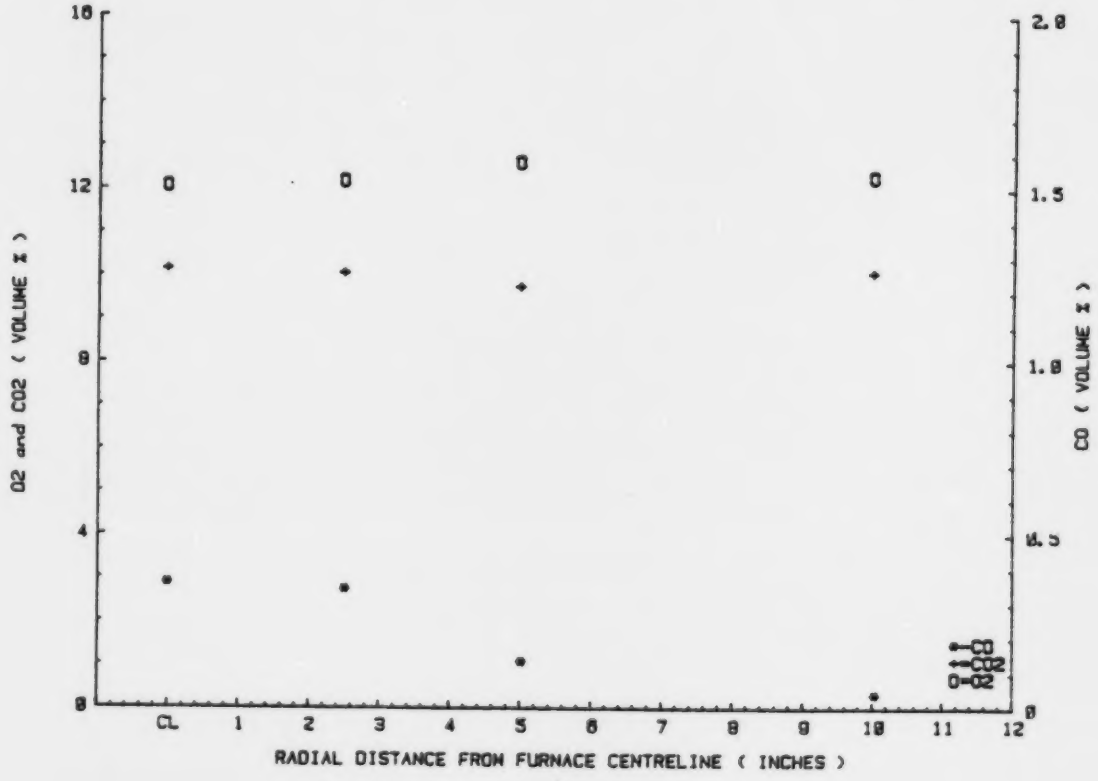


Figure 63 AIII: 25 Wt % Coal (minus 10 mesh) in Tar (6 lb/min Injection Rate)

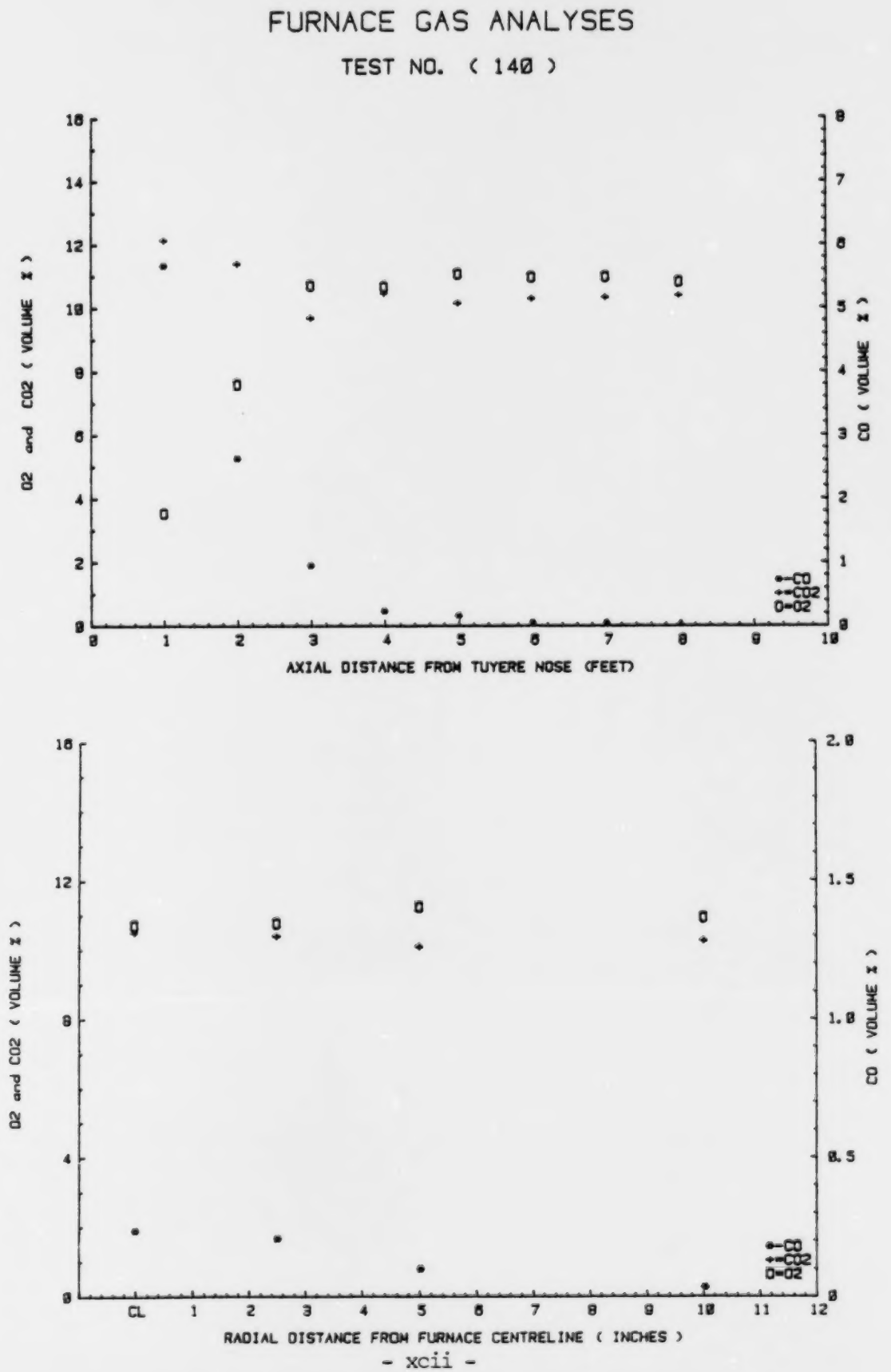


Figure 64 AIII: 50 Wt % Coal (minus 10 mesh) in Tar (4.5 lb/min Injection Rate)

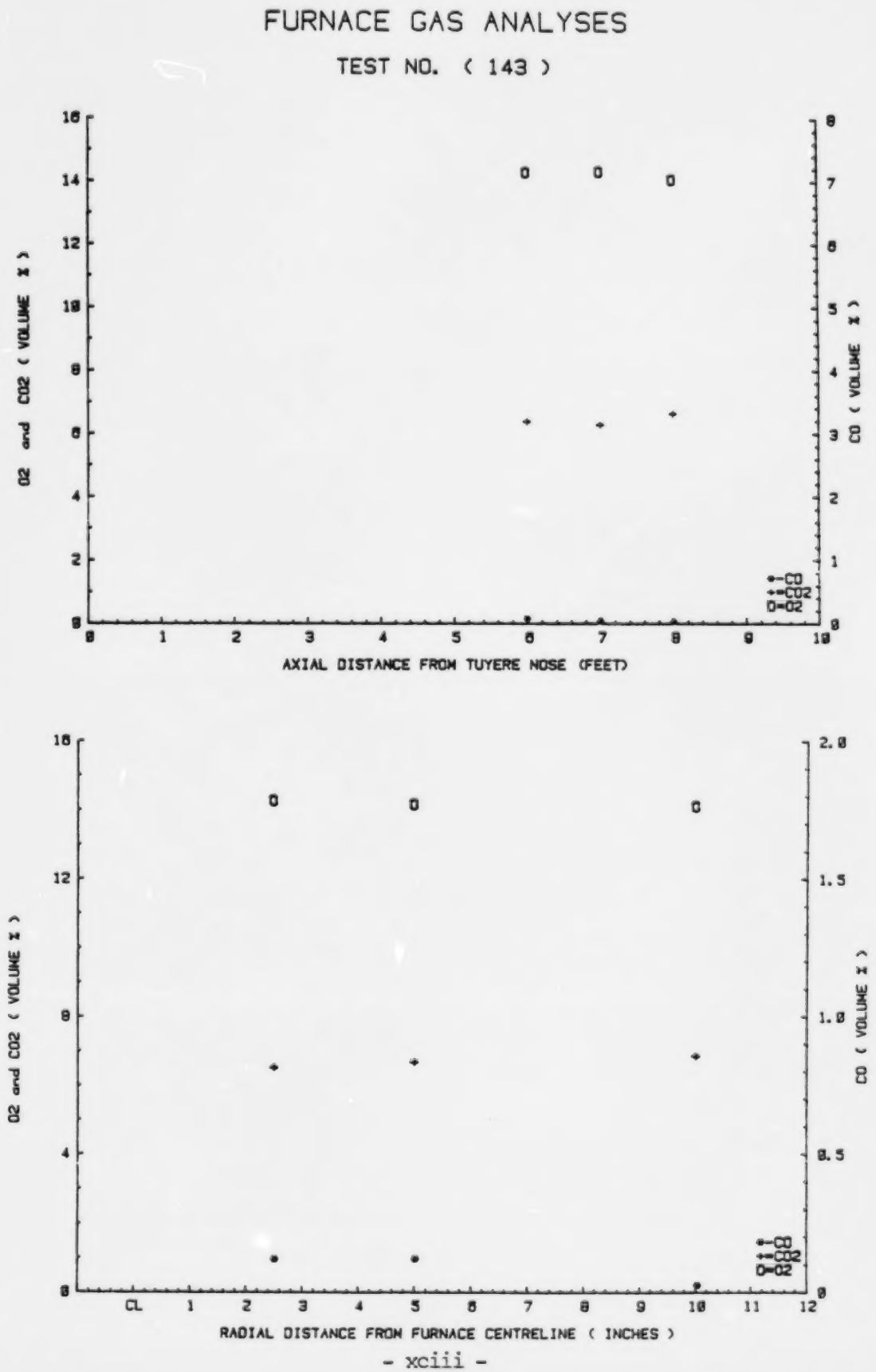
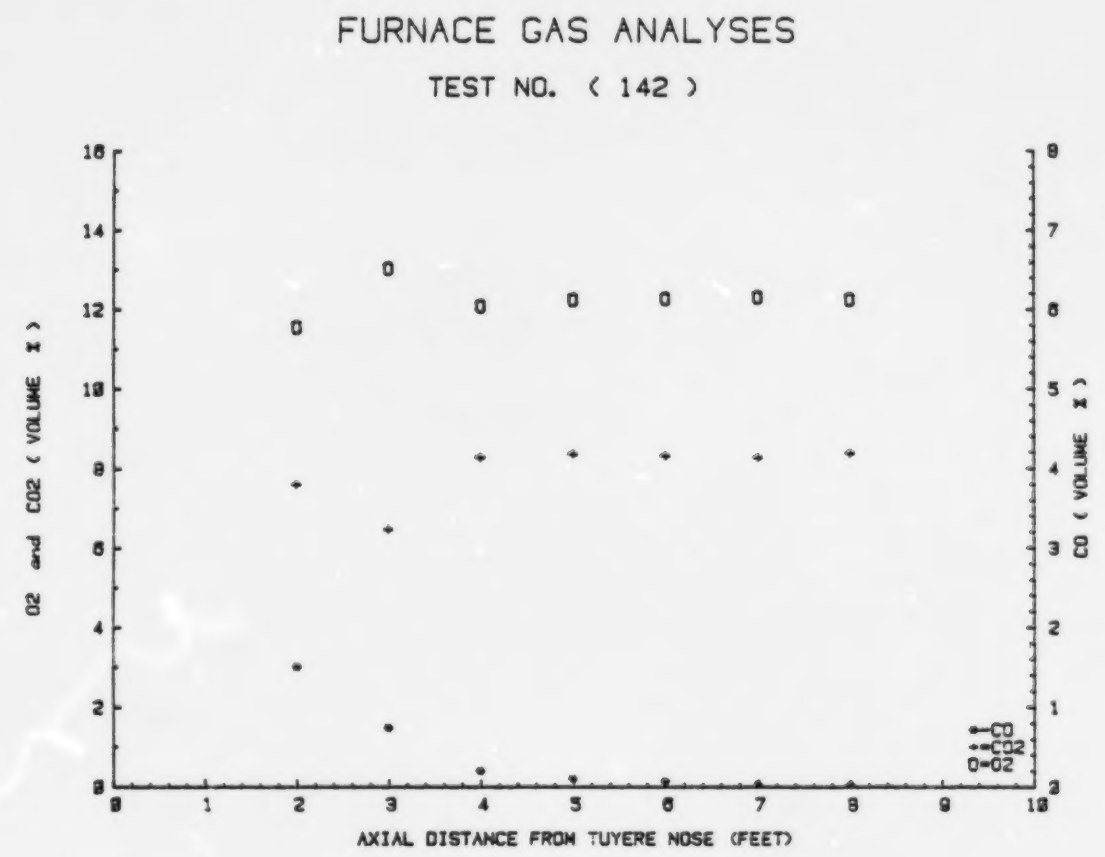
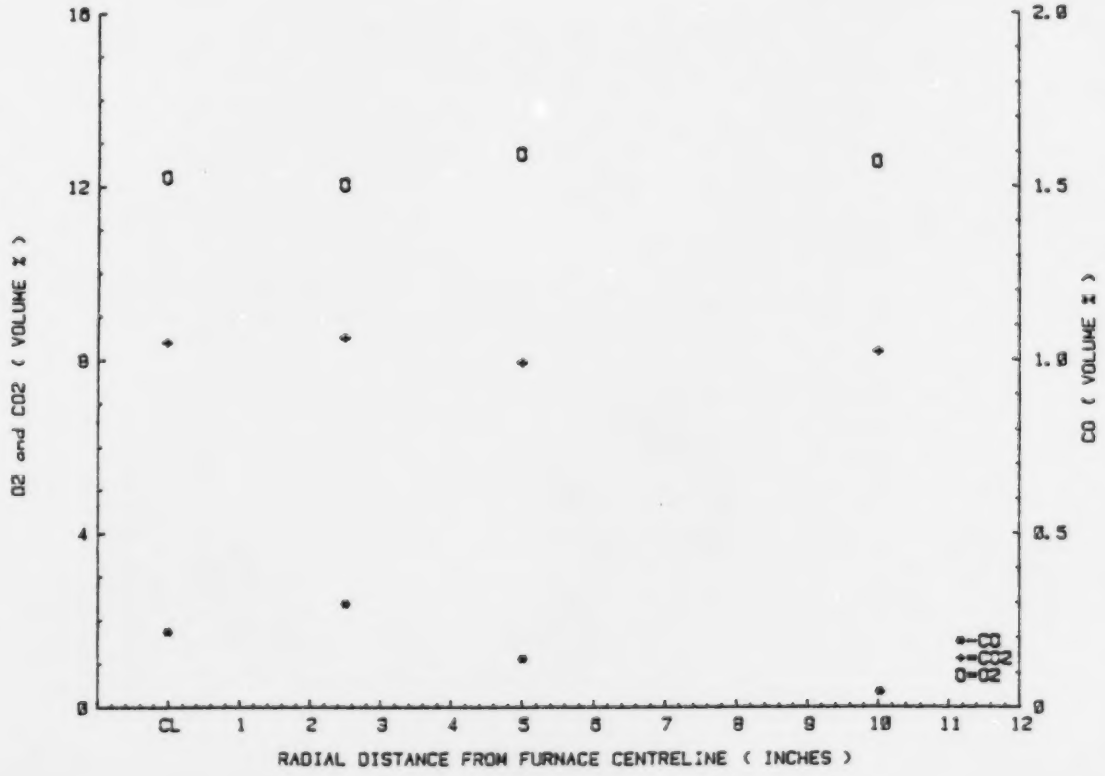

FURNACE GAS ANALYSES
TEST NO. (143)
O2 and CO2 (VOLUME %)
CO (VOLUME %)
AXIAL DISTANCE FROM TUYERE NOSE (FEET)
CO
CO2
O2
RADIAL DISTANCE FROM FURNACE CENTRELINE (INCHES)

Figure 65 AIII: 50 Wt % Coal (minus 10 mesh) in Tar (6 lb/min Injection Rate)





APPENDIX IV

'C' FURNACE SLURRY INJECTION FACILITY

The reference drawings related to this scope of work are listed below:-

Facility Code	Title
21017996001	General Layout of Facility
21017796005	Details of Slurry Mixing Tanks
21017796006	Piping Layout of Facility

This scope of work only covers the known requirements of the Full Furnace Coal Slurry Injection Facility.

The scope includes special notes on aspects of the job which require further engineering. By scoping the work in this manner, related areas of relatively complete and incomplete engineering can be compared more easily.

The proposed coal/slurry injection facility incorporates the equipment necessary to transport the raw coal, process it ready for the slurry, feed the mixing tanks and pump the resulting slurry into the furnace. The required components are listed below:-

A) Coal Handling Equipment
B) Coal Processing Equipment
C) Fuel Oil Supply, Propane Supply
D) Slurrying Equipment
E) Coal Processing and Slurrying Building
F) Injection Equipment
G) Steam and Water Supply
H) Electrical Power Supply and Equipment
I) Measurement and Control Equipment
J) Rented Equipment

In addition to the above equipment, the scope of work includes a "test failure" contingency. This requires that the components outlined above will be removed from the site and suitably disposed of if the project is unsuccessful.

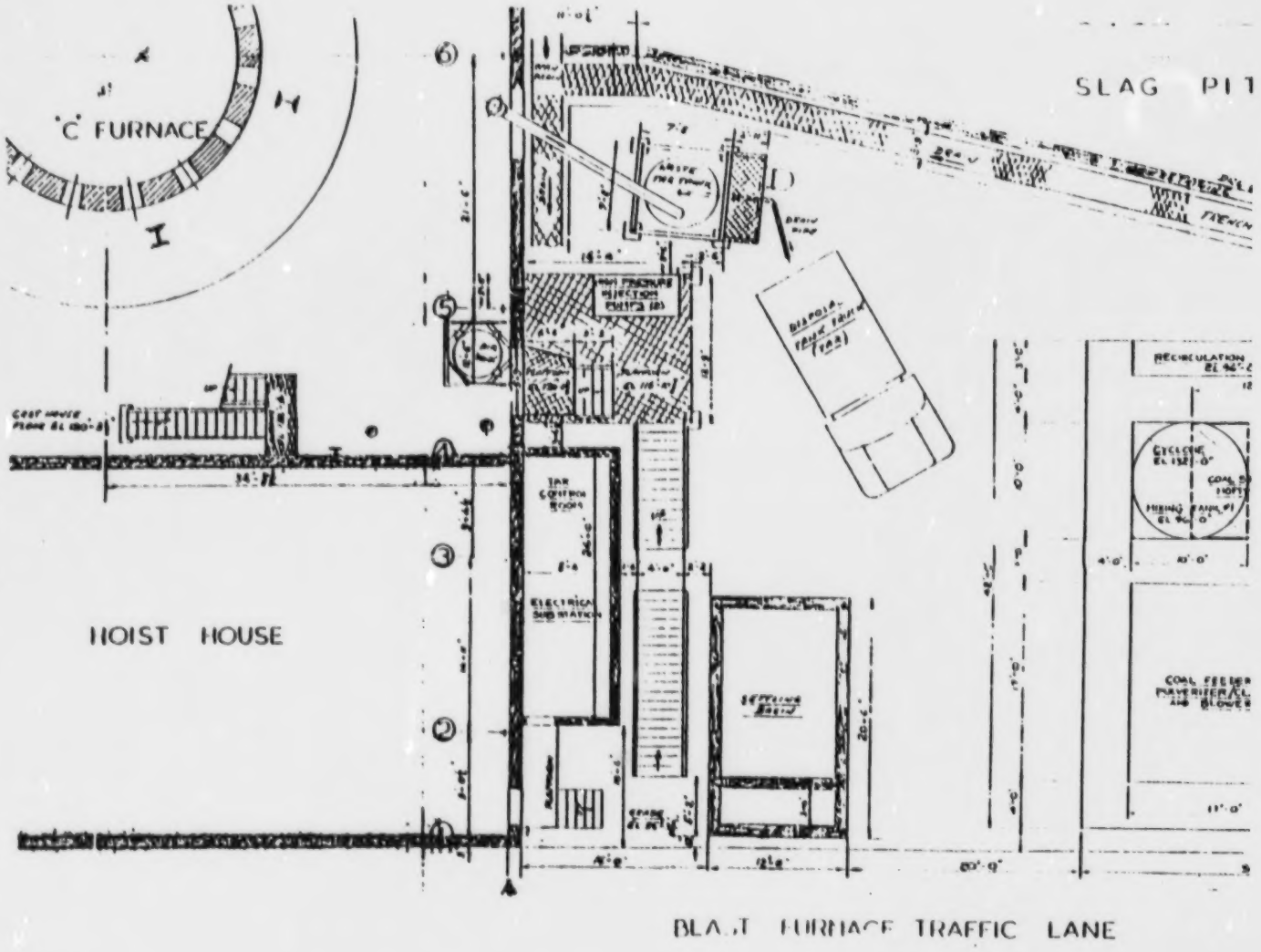
The following descriptions marked with an asterisk (*) indicate that the subject matter had similar details in the previous Report (No. 770098).

A) Coal Handling Equipment as shown in Drawing 21017996001 will include the following:-

a) * One Coal Storage Box with

- 12' W x 22' L. x 5' H. dimensions
- 15 ton coal capacity
- open top and end
- 1/2" H.R.S. plate welded construction with external framing
- no foundations required

Figure 1 AIV: Layout of Coal Slurry Facility for 'C' Furnace



b) * One Belt Feeding Coal Hopper

- dimensions unknown
- 2 front end loader bucket capacity
- open top and end
- 3/8" H.R.S. plate welded construction with external framing
- concrete foundations
- ladder to external hopper access platform for scaling freeze-ups

c) One Belt Converyor Assembly

- 18" wide belt conveyor, approximately 64 ft. long
- driven by a 3 HP, 1160 RPM, TEFC motor and a Hamilton Gear Ltd. single reduction unit, Type BF59, 70:1 ratio
- 18" wide belt of Good Year 'Playton 210', Style B quality
- 20° troughing idlers, impact idlers at loading end
- 16" diameter end pulleys, rubber lagged driven pulley
- screw take-up and spring loaded scraper
- supporting structure and foundations

d) One Receiving Hopper

- dimensions not determined
- required to chute conveyor discharge into coal feeder
- sealed to frame in building so hopper wall temperature is ambient outside temperature

B) Coal Processing Equipment as shown in Drawing 21017996001, will consist of the following equipment:-

a) One Coal Feeder which has not been specified by the supplier but which would be similar to one supplied by:

Stock Equipment Co.

70'-0" Gravimetric Pressurized Feeder with:

- 24" RR-VB-SP feeder inlet valve
- 10'-0" long x 24-3/4" O.D. downspout
- two (2) presser couplings
- feeder discharge hopper
- 16" O.D. - downspout
- 2 HP explosion-proof drive motor
- 1.4 HP cleanout conveyor motor

b) One Pulverizer/Classifier as detailed by Combustion Engineering of Brantford is a #593 Raymond Bowl Mill or equivalent. This package requires an electric motor and gear reducer (both supplied by Stelco) with the following specifications.

200 HP - 1800 RPM - 3 P. - 550 V with 2:1 speed reduction

The power supply is controlled from the tar control room with a manual override at the motor location.

c) One inert gas generator which will "make-up" approximately 10% of the inert gas (1300 scfm). A supplier has not detailed this unit. However, a similar system has the following characteristics:-

130 cf, make-up air flow
40% excess air from burner

15 - 20 HP fan motor

d) One cyclone with a 10 ft. diameter and vertical length of 20 ft. from top to cone bottom, capable of an air flow of 13,000 cfm. A rotary airlock valve at the bottom is powered by a 1 HP explosion-proof motor.

e) One centrifugal fan with a flow rate of 13,000 cfm, powered by a 100 HP, 3 Ø, 550 V, 1800 RPM E.P. electric motor.

f) One baghouse as recommended by Wheelabrator Corp. of Canada, Ltd. with the following features:-

Pulse Type #1212, Model 120
Nomex bags = 16 oz.
Cloth footage = 144 bag with 2826 ft.^{2} area
Explosion-proof electrics
Explosion release panels
Clean side bag access
Rotary valve with 2 HP drive
Dimensions 8'-4" x 8'-4" inside
20'-8" housing height
6'-6" hopper weight

27'-2" total height

Weight empty = 9000 lbs.

g) One centrifugal pressurizing fan to provide the Jet Pulse bag filter (item f) with 15 cfm inert "clean side" gas @ 80-90 psi

h) One storage hopper with venting to the baghouse. The pulverized coal capacity has not been determined. To conform to the sizes of the other equipment, the hopper should be approximately 8'-0" x 8'-0" in section. The outlet rotary air lock valve will be powered by a 1 HP E.P. electric motor.

*A breeching chute with a gas-tight seal to the slurry tanks (Item D). This is controlled from ground level by a chain-driven directional flop gate.

C) Fuel Oil and Enriched Coke Oven Gas Supply

Fuel oil is tapped from the Blast Furnace "C" supply lines and bled to the slurry tanks (item D) in an insulated steam traced 2-1/2" I.D. pipe. The flow into the slurry tanks is controlled by (item I):-

a) Manual override valves (2 required)
b) Automatic slurry level switch (2 required)
c) Remote control from Tar Control Room

Fuel oil is piped from the slurry line to the inert gas supply burner. Manual shut-off and a pressure regulator will likely be required.

The enriched coke oven gas supply is required with the "interrupted pilot" device suggested by the supplier. This supply would be metered into a 1" I.D. line from the "C" Furnace supply. A different type of burner may not require this piloting.

D) * Slurrying Equipment

The slurry equipment consists of two batch mixing tanks, 10 ft. diameter x 12 ft. high, H.R.S. steel plate construction with gas-tight lids and venting to the baghouse. The tanks are insulated and steam heated from the bottom. Details of the construction are similar to those presented in Drawing 21017796005 (note that the drawing was made in 1977).

The two mixers have not been specified but they will be controlled from the control room with manual overrides at tank side.

The tanks are placed on electronic load cells which are interfaced with the appropriate instruments in the control room.

E) Coal Processing and Slurrying Building

The coal processing equipment (Item C) and slurrying equipment (Item D) are enclosed in a building. The ground floor area will be 32'-0" x 42'-0" as shown in Drawing 21017996001. The building must be approximately 56'-0" high to support the proposed stack of equipment. (This equipment includes the tandem arrangement of cyclone (Item B-d) and baghouse (Item B-f), both emptying into the storage silo (Item B-h) which is gated into either of the two batch slurry tanks (Item D) located at ground level.) Crane access is required for installation of the equipment.

The possibility of an explosion requires the addition of explosion release panels on the building. In addition, sufficient strength must be provided in the walls facing the slag pit to withstand the impact of debris (in the event of an explosion). The latter requirement may foreshadow the impracticality of the location of the entire facility. This was noted in the covering letter.

F) Injection Equipment

The injection equipment consists of a low pressure recirculating system feeding a high pressure injection system. A piping arrangement similar to that shown in Drawing 21017796006 is proposed. The componentss used are listed as follows:-

a) 2 Worthington "M" Centrifugal Slurry pumps (Model 2-1/2 M091-NI Hard) will be used with an appropriate parallel piping network to drive the recirculated slurry.

*b) A loop of 2-1/2" diameter slurry pipe which come from either slurry tank through the pump system, to the link-up with the injection piping and back to the appropriate slurry tank.

c) 2 Worthington Horizontal Duplex Steam driven pumps (Model 4-1/2 x 2-3/3 x 4 VC) will be used for the high pressure injection system.

d) A piping hose and valve arrangement similar to the tar injection system for Blast Furnace "C" will be used.

G) Steam and Water Supply

A steam supply and lines will be required for the following:-

*a) Tracing fuel oil (Item C), slurry recirculating and water piping.

*b) Heating the bottom of both slurry tanks (Item D).

c) Driving the high pressure slurry pumps (Item F-c).

*d) Purging the fuel oil (Item C) and slurry injection equipment (Item F).

A water supply with spray head is required to put a drying load on the inert gas system at start-up.

H) Electrical Power Supply & Equipment

An addition to the "C" Furnace electrical substation may be required for an adequate power supply to the facility.

Equipment:-

a) 8 E.P. electric motors, each over 5 HP, totalling 405 HP.

b) 5 E.P. electric motors, each 2 HP or less, totalling approximately 7 HP.

c) Explosion-proof electrical lighting for inside the process building (Item E).

d) Electrical lighting for the coal hopper and storage box.

The items listed in a) to d) inclusive, with the exception of two 30 HP motors and two 7-1/2 HP motors are to be supplied by Stelco.

I) Measurement and Control Equipment

A control panel will be located in the Tar Control Room. The panel will be linked with the following equipment:-

*a) 2 sets of slurry tank load cells (the signals must be digitalized by the control panel).

b) On/off switches for the process equipment.

c) 4 temperature sensors for the inert gas ducts.

*d) 2 temperature sensors for the batch slurry tanks (1 temperature probe for each).

e) Automatic water spray valve.

*f) 2 high slurry level monitors.

*g) 2 high slurry level monitors.

*h) Automatic control valve for oil supply.

*i) Automatic control valve for the slurry.

*j) 15 automatic shut off valves for the 15 slurry down comers at the furnace.

*k) Slurry weight recording device to record data from load cells (Item a).

J) Rented Equipment

*a) One front end loader.

*b) One dump truck.

WCB:CLJ
Works Engineering
December 5, 1979

APPENDIX V

SLURRY PUMPING TRIAL

Pump Selection

The major task in designing the pumping facility was to select the pumps with the greatest chance of succeeding in our proposed application. Pump selection was based on the following physical requirements:

- the slurry will consist of a maximum of 50 percent by weight of coal in tar,
- the coal top size will be 8 mesh,
- the slurry will have a maximum viscosity of 1000 centipoises,
- the slurry specific gravity will be in the range of 1.2 to 1.4,
- the recirculation loop will be sized for a pump of 50 USGPM capacity,
- the high pressure injection loop will be sized for a pump of 9 to 29 USGPM capacity,
- the high pressure injection loop will operate at (a maximum of) 250 psi,
- the linear velocity of the slurry in the pipelines must be at least 4 ft/sec, to preclude the settling of coal in the line, and
- the slurry temperature will be between 180 and 200°F.

We also considered:

- the potential for using the same pump throughout the three proposed stages of slurry fuel development,
- the predicted reliability from a maintenance and wear standpoint,

- Stelco's experience with similar models, and
- cost.

The two major pump classifications examined were centrifugal and positive displacement pumps. The relative merits of seven pumps within these broad categories are given in Table I AV.

Table I AV: Pump Characteristics

Pump Type	Advantages	Disadvantages	Comments
Centrifugal:			
Horizontal	• low maintenance • low initial cost (~$3000) • high degree of acceptability by operators	• limited head capabilities • low efficiencies • a flushing liquid is required for packing	Centrifugal pumps (of the slurry nature) have been successfully used in Stelco's By-Product Plant and Central Boiler Station to pump tar. Has split casing for easy maintenance and built-in wear plates.
Vertical	• low maintenance • low initial cost (~$5000) • accepted by operators in special situations • no flushing liquid is required for packings	• limited head capabilities • low efficiencies	Should be mounted over or in tank. Nature of pump has it in an awkward location for maintenance. Uses a vertical motor. No provisions for wear plates. Must be physically removed to rebuild.
Positive Displacement:			
Piston Pump	• relatively low maintenance • long life of pump • high pressures capable at low volumes • low initial cost (~$4500) • low velocity (linear) of piston • low velocity of fluid through valves • steam powered	• valves require periodic maintenance • a surge suppressor is required	Pumps of this nature used successfully to transfer tar at Stelco for ~30 years and are still in operation
Plunger Pump	• capable of (not specifically designed for) high pressures at low volumes • accessibility to valves good • low maintenance other than valves and packing	• very high cost ($25 000) • number of moving parts high • relatively high linear velocity of plunger • relatively high velocity of fluid through valves • a surge suppressor is required	Algoma reportedly uses this style of pump to transfer tar in their By-Product Plant. Stelco (By-Product Plant) has just ordered one for a trial to pump tar.
Gear Pump	• high pressures at low volumes • low initial cost • simple design • easy maintenance	• fluid to be pumped must not be abrasive or gear will wear	"Viking" model gear pumps were used to transfer tar in the Central Boiler Station and wore out.
Moyno Pump	• high pressure, low volume capability • no surge suppressor necessary	• high cost (for specialized pump) • rotor, stator tends to grind up coal • there is a great deal of fluid contact with the rotor and stator	The large amount of slurry contact with rotor and stator will accelerate wear.
Diaphragm Pump	• low cost • good volume versus pressure characteristics	• construction of pumps generally not suited for heavy industry pressures • volumes suitable for testing and first trial only; not suitable for final furnace application • maintenance on valves and diaphragm would appear frequent. A surge suppressor is required	Generally these pumps are used for light applications since their portability is an asset. They do not appear suitable for heavy industrial service.

During our coal slurry program we used three pumps (Table II AV). For a blast furnace injection system, we recommend the piston steam pump and the centrifugal pump.

Table II AV: Slurry Pumps Tested

Pump	Use	Hours of Operation	Comments
Worthington Centrifugal	Pump Trial	2000	• seals leaked • expect at least two years of maintenance-free operation
Worthington Duplex Piston Steam	Pump Trial	1800	• seals leaked • expect at least one year of maintenance-free operation
Moyno	Rheology Trial Combustion Trial	800	• loss of head • difficult to free when seized

Pump Trial

The slurry tank was charged with 50 wt percent minus 10 mesh coal in No 6C oil. Tar was not used as ventilation would have been required to remove the tar fumes.

Water leaked from the centrifugal pump gland into the pump. As a result, the slurry became diluted with water and the tank filled. To remove the water and to maintain a constant slurry level in the tank, we made several modifications:

- a vent was added to the tank to allow water vapor to escape,
- a needle valve, rotameter, and strainer were added to the centrifugal pump seal water line to give better control over water flow to the seal,
- two traps were installed on the drain from the centrifugal pump seal to prevent the drain from plugging with slurry and to prevent slurry from entering the plant drains, and
- water cooling was added to control slurry temperature by removing excess heat generated by the mixer and pumps.

These modifications, combined with careful manipulation of tank temperature, seal water flow, and gland tightness, allowed the slurry level and moisture to be controlled.

After several weeks of pumping, the slurry became viscous, causing pumping and mixing difficulties. To eliminate these problems a small amount of No 6C oil was added and the pumping continued until difficulties were encountered a second time. At this time, the slurry was replaced with a new batch.

Three slurry batches and two oil additions were used during this trial. The first batch was pumped for 36 days with an oil addition after 26 days. The second batch was pumped for 34 days with an oil addition after 20 days. The third batch was pumped for 22 days, after which the trial ended. An oil addition would have been required had the trial continued.

We believe that distillation of the light oil fractions caused the increase in slurry viscosity. The distilled fractions escaped through the vent used to allow water vapor to escape. This problem will occur whenever a heated slurry is stored in a vented tank for more than a couple of weeks.

A slurry sample was taken from the second batch of slurry when difficulty with pumping was experienced. At the time the sample was taken, the centrifugal pump would pump for 10 to 15 minutes and then stop. If the pump and stirrer were shut off and restarted, the centrifugal pump would again operate for another 10 to 15 minutes. The duplex pump handled this slurry without difficulty as long as slurry was available on the suction side.

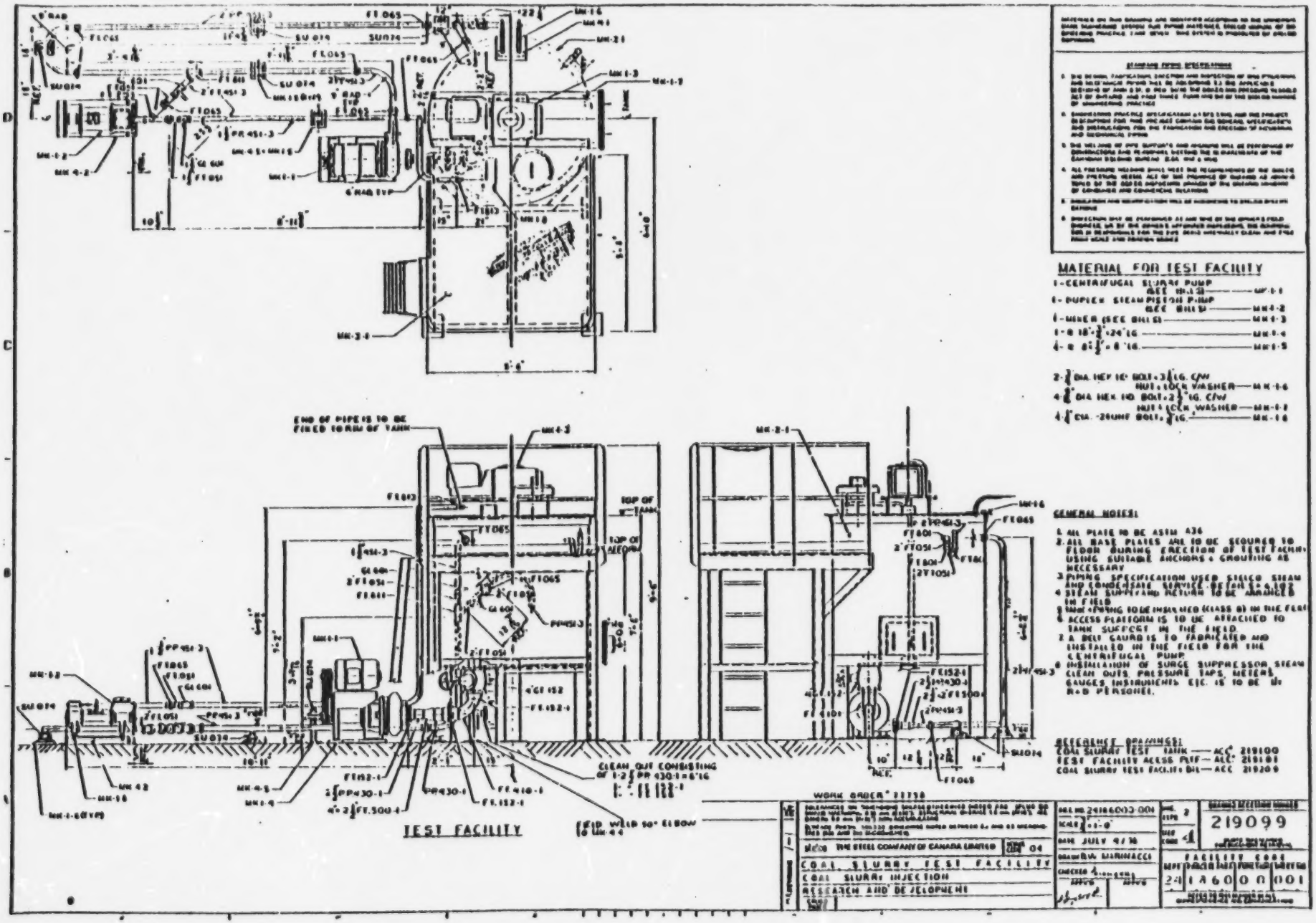
This slurry had the consistency of grease. When it was placed in a beaker and stirred at 200°F, the slurry sheared at the glass/slurry interface and rotated as a solid mass. The Brookfield viscometer spindle formed a depression when placed in the slurry. By placing slurry over the spindle, a viscosity of 31 500 cp at 200°F was measured. This is more than 30 times the pump fixture design requirements of 1000 cp.

The slurry, at this viscosity, was at the limit of the handling capability of the centrifugal pump. The duplex pump was quite capable of pumping this slurry.

A steel flex hose was initially used to join the duplex pump to the injection lance. This hose failed in less than a week and was replaced by a second flex hose which also failed in less than a week. These hoses failed in fatigue. The flex hose was replaced with a formed pipe, and the problem was eliminated.

The general piping layout is shown in figure 1 AV. The valves specified in the drawing were changed from globe valves to gate valves for slurry service. These valves were either fully open or fully closed and did not show any significant wear on the internal surfaces.

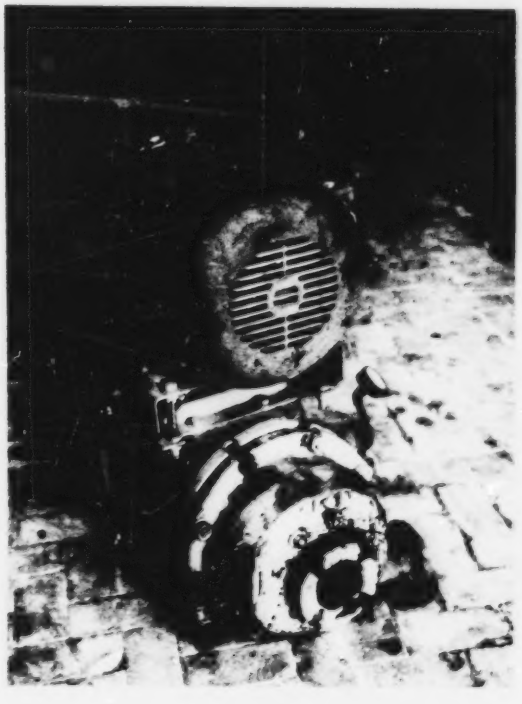
Figure 1 AV: Pump Test Facility



Worthington
Centrifugal Pump

The Worthington "Type M" Slurry Pump, figure 2 AV, is a single-stage end-suction centrifugal pump designed for pumping slurries and abrasive mixtures.

Figure 2 AV: Worthington "Type M"
Centrifugal Slurry Pump



The pump casings have a tangential discharge and horizontal inlet. Two replaceable wear plates are provided, one on the suction side and the other on the gland side. The impeller vanes are rounded at the inlet and have extra thickness at the tips to compensate for wear. Hydrodynamic vanes are provided on both the suction and gland side to reduce the hydraulic axial load and to minimize wear.

Figure 3 AV shows the impeller mounted on the drive shaft with the gland wear plate and rubber sealing ring in place. Some rounding of the hydrodynamic vanes is evident, but the impeller is in good condition.

Figure 3 AV: Worthington "Type M" Slurry Pump with Impeller, Gland Wear Plate and Gland Circumferential Rubber Seal

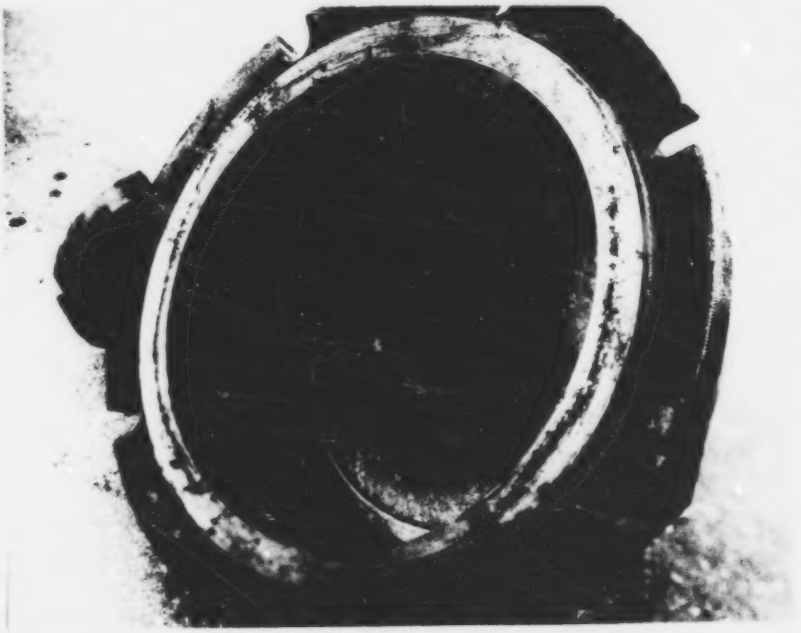
The tips of the impeller vanes, where wear is mot likely to occur, are shown in figure 4 AV. The used impeller shows slight smoothing of the cast tip. Rounding of the hydrodynamic vanes is also evident, but is not substantial.

Figure 4 AV: Impeller Vanes

USED NEW

The centrifugal pump's casing, showing the horizontal inlet and tangential outlet, is shown in figure 5 AV.

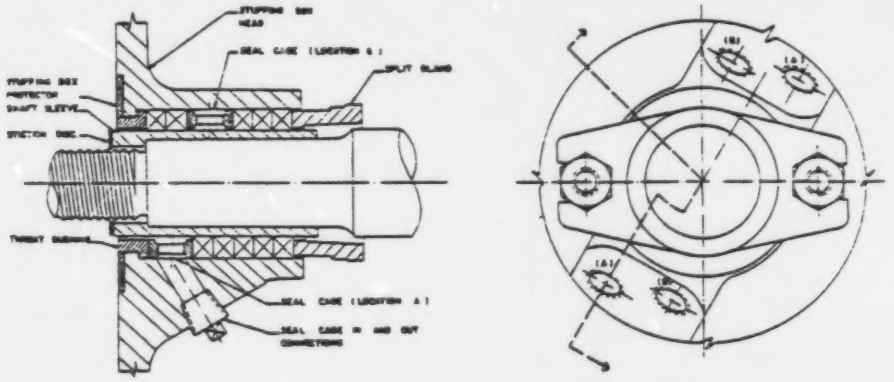
Figure 5 AV: Centrifugal Pump Casing with Suction Wear Plate in Place



The casing at the tangential outlet shows some smoothing of the cast surface, but no appreciable thinning of the casing thickness has occurred. These results indicate that the pump casing should last for years in this type of slurry service.

The stuffing box was the only part of the centrifugal pump that required maintenance during the trial. A diagram of the stuffing box is shown in figure 6 AV.

Figure 6 AV: Worthington "Type M" Slurry Pump Stuffing Box



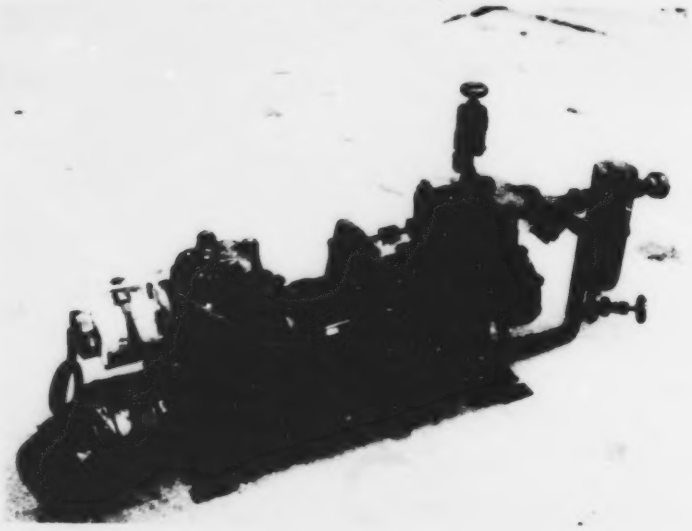
The seal cage was in location B for this trial, in order to keep the leakage of flushing water into the pump as low as possible. Even small leakages of water into a closed loop system are extremely troublesome. To control the leakage, four complete changes of packing were used during the trial.

Another problem encountered during the trial was slurry leaking into the seal flushing water drain. This would occur on a slurry injection system if the flushing pressure became too low. For our test facility, this leakage was due to bay water sediment fouling a needle valve.

Worthington
Horizontal Duplex
Piston Steam Pump

The Worthington Horizontal Duplex Piston Steam Pump, figure 7 AV, consists essentially of two single pumps arranged side by side.

Figure 7 AV: Worthington Horizontal Duplex Piston Steam Pump



A slide valve arrangement connected by levers to the piston rods of each pump controls the movement of the piston. The piston rod of one side, in making its stroke, controls the valve movement which admits steam into the cylinder of the other side. The slide valve mechanism is so arranged that one of the steam ports is always open. This means there is no dead point and the pump is always ready to start.

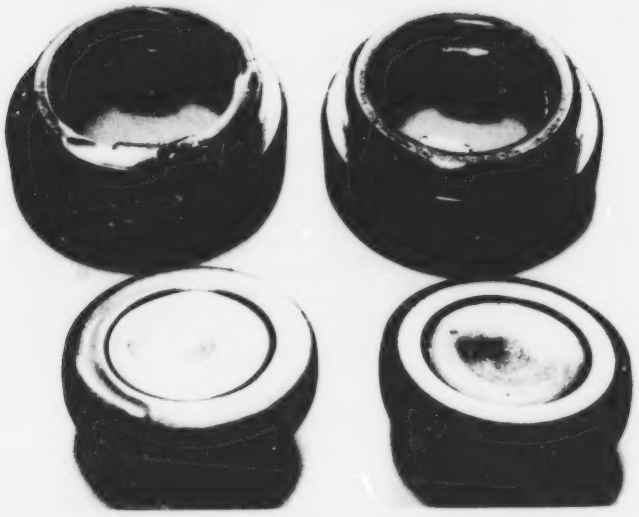
At the end of the trial, after 1842 hours of slurry service, the slurry end of the Duplex pump was dismantled and examined for wear.

Slurry flow is controlled by eight valves, two inlet and two outlet for each side. The valve assembly is shown in figure 8 AV.

Figure 8 AV: Disc Valve Assembly

Six of the eight valves were found to be in excellent condition with little wear on either the valve seat or valve disc; however, two valves, one inlet and one outlet, had broken valve seats. Figure 9 AV shows one good and one broken valve seat with accompanying disc valve. The sharpness and shape of the area where the metal has been removed from the broken valve seat indicates a fracture rather than wear. This fracture was probably caused by quench cracking of the valve seat during heat treatment.

Figure 9 AV: Duplex Pump Valve Seats and Disc Valves



USED NEW

Checking the valve seats for flaws by magnetic particle and ultrasonic inspection before installation should eliminate this problem.

Most of the springs that help seat the disc valves broke during service. Figure 10 AV shows two springs, one of which is broken.

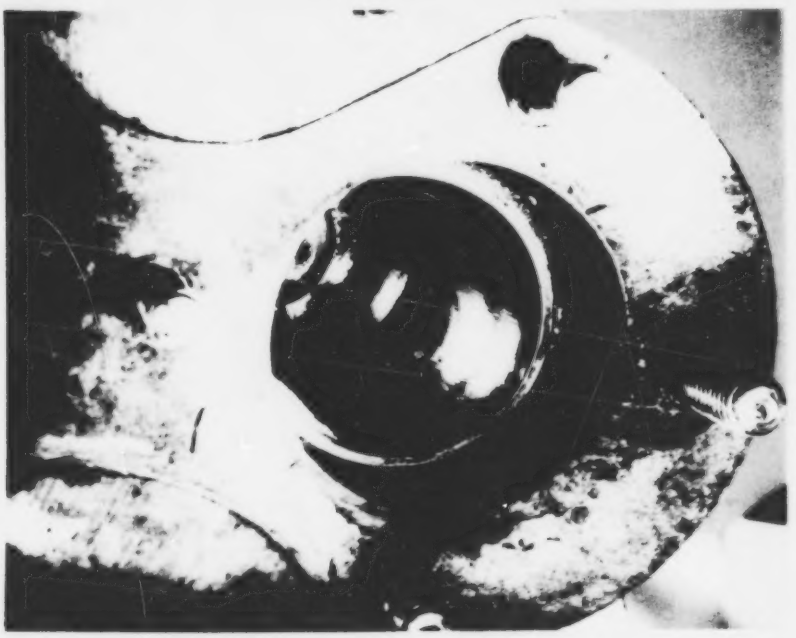
Figure 10 AV: Disc Valve Springs

NEW USED

These valve springs are too light for use in slurry service. The duplex pump worked well even though the springs were broken, suggesting that the springs are not necessary for the valves to function properly.

The surface of the hardened cylinder liners had longitudinal scoring, as shown in figure 11 AV. This scoring is not sufficient to significantly reduce pump efficiency; however, the cylinder liners will need to be replaced periodically. An estimate of one year of slurry service seems reasonable from these results.

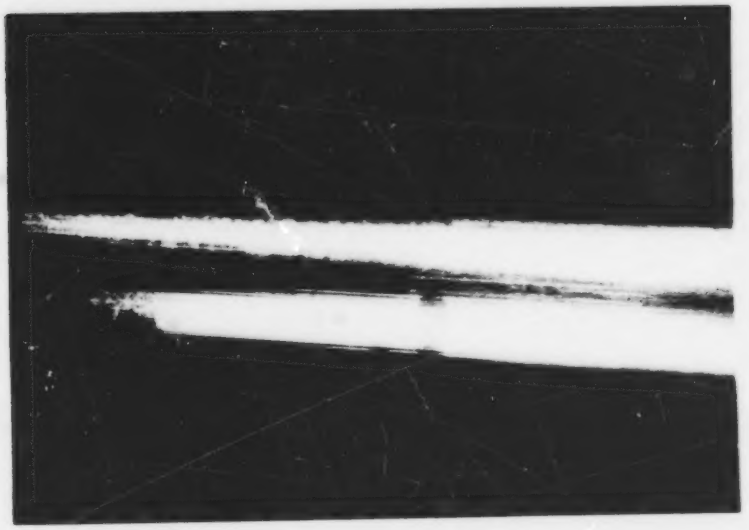
Figure 11 AV: Scored Stainless Steel Cylinder Liner



The pistons and pump cavities were in very good condition. Annual replacement of the piston rings would be required. The pump casting is expected to last many years.

During the pumping trials the two slurry stuffing boxes leaked excessively. A new packing ring was required every few days and the gland required tightening several times in each 24-hour period. Examination of the piston rods at the end of the trial revealed scoring in the area where the rods passed through the stuffing box (figure 12 AV).

Figure 12 AV: Piston Rod Showing Scoring



This explains the difficulty in keeping a seal and indicates the need for piston rods made from a more wear-resistant steel for slurry service.

The leaking seal problem emphasizes the need for mounting this pump with catch basins and with adequate access to the slurry stuffing boxes for maintenance.

Moyno Pump

The Moyno pump was first used for the viscosity trials and later for the combustion trials. The pump had a steel rotor and stator and was rated at 10 Igpm at 300 rpm.

During the viscosity trials the pump operated with a constant head and no slippage of fluid through the pump was noted; however, for the combustion trials, slippage of the pure fluids (oil and tar) was noted. The slippage decreased and was eventually eliminated as the fluid viscosities increased upon addition of coal. Failure of the variable speed drive caused the pump to plug during the viscosity trials. The pump was easily freed by manually turning the drive shaft while heating the pump to reduce the slurry viscosity (a slurry of minus 100 mesh coal in tar at the time of plugging).

Improper anchoring of the pump caused it to seize during the combustion trials. On these occasions, freeing the pump was extremely difficult. The slurries, on these occasions, were 50 wt percent of minus 35 or minus 10 mesh coal in either No 6P oil or tar at 180°F. Freeing the pump when it is seized with coarse coal is much more difficult then freeing it when it is seized with fine coal.

APPENDIX VI

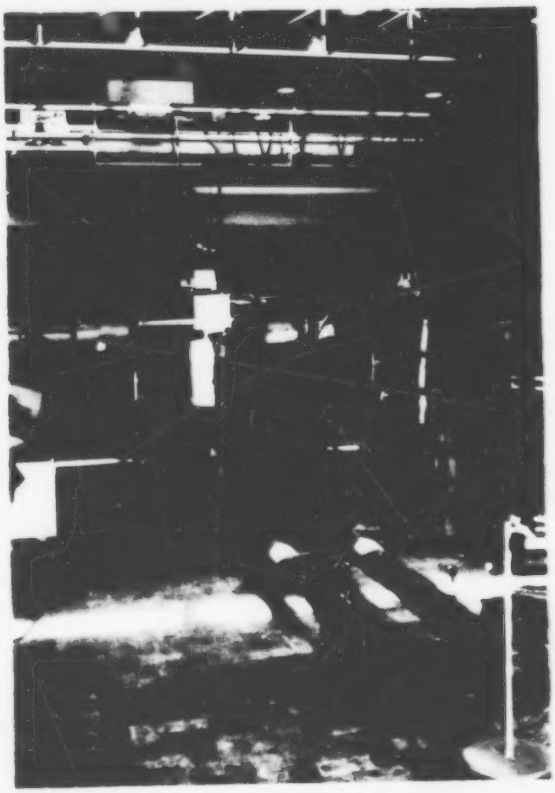
SLURRY RHEOLOGY

We studied slurry rheology primarily to establish the empirical relationships that could be used to design a slurry injection system. In particular, we wished to develop a simple model for predicting slurry viscosities over a broad range of slurry conditions (fluid type, coal size, coal concentration, slurry temperature).

Slurry Test Loop

Slurry rheology was studied with the test loop pictured in figure 1 AVI.

Figure 1 AVI: Slurry Test Loop

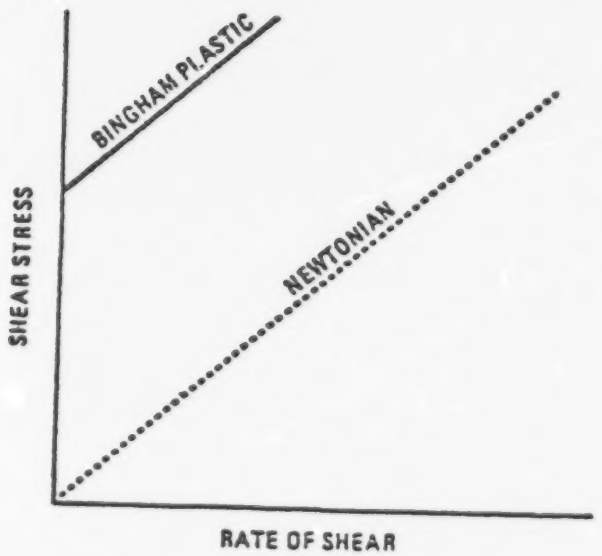


The loop consisted of a 300 gallon steam-heated tank, a Lightnin' Mixer, a Moyno pump with steel rotor and stator, a variable speed drive, and a 50 ft, traced and insulated, 1in pipeline fitted with pressure taps at 10 ft intervals. With this loop batched slurries at different coal concentrations, coal sizes, temperatures, and flow rates were evaluated.

Slurry Characterization

Starting with the no-coal case, the pressure drops across the 10 ft segments of the loop were recorded at a minimum of four flow rates in the range 0.75 to 5 ft/sec (∿1.5 to 12 Igpm). Varying the flow rates enabled us to determine if the slurries were Newtonian (i.e. a linear relationship between shear rate and shear stress, combined with a zero intercept, as in figure 2 AVI).

Figure 2 AVI: Shear Stress-Shear Rate Curves for Typical Time Independent Non-Newtonian Fluids



If the slurry exhibits a linear relationship between shear stress and shear rate, yet has a non-zero intercept (yield stress), then the slurry can be characterized as a Bingham Plastic.

For a Newtonian fluid, the slope of the shear stress versus shear rate line is the fluid viscosity, μ:

$$\mu_{Newtonian} = \frac{\Delta \text{ Shear Stress}}{\Delta \text{ Shear Rate}}$$

The shear stress, τ_ω, is a function of the pipe diameter, D, and the pressure drop, $\Delta P/L$, where:

$$\tau_\omega = \frac{D}{4} \frac{\Delta P}{L}$$

The shear rate, du/dy, is a function of the flow velocity, u, and the pipe diameter, where:

$$\frac{du}{dy} = \frac{8u}{D}$$

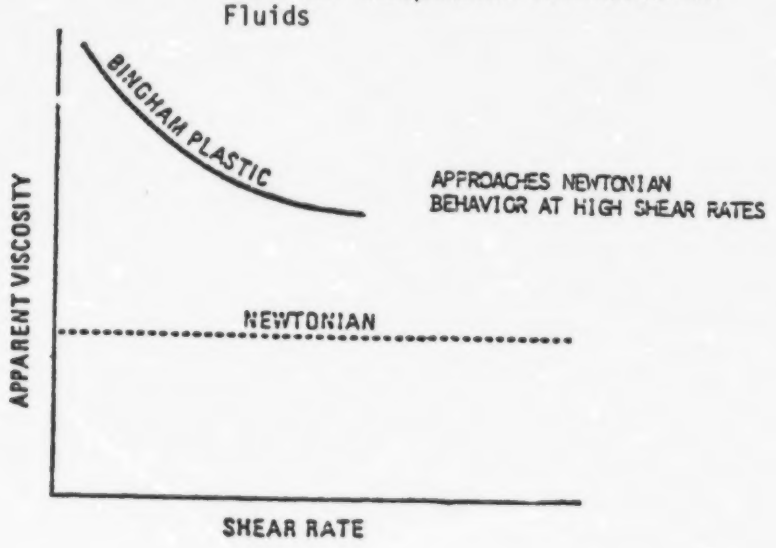
For a Bingham Plastic, the viscosity is given by:[8]

$$\mu = 1000 \quad S + \frac{3/4 \ \tau_{w_o} D}{6 \mu} \qquad \text{.....(1 AVI)}$$

where: μ = viscosity, cp
τ_{w_o} = wall shear stress extrapolated to zero shear rate, N/m^2
D = pipe diameter, m
u = linear velocity, m/sec
S = slope of line, $N \cdot sec/m^2$

When τ_{w_o} is zero (i.e. the intercept is zero), the straight Newtonian case exists. Also, as the flow rate increases, i.e. as μ approaches infinity, the second term on the right-hand side of Equation 1 AVI approaches zero. At high flow (shear) rates, Bingham Plastic fluids revert to Newtonian behavior (figure 3 AVI).

Figure 3 AVI: Apparent Viscosity versus Shear Rate for Time Independent Non-Newtonian Fluids



Thus, a Bingham Plastic fluid may be characterized simply by saying that it exhibits a yield stress and then reverts to Newtonian behavior. The yield stress is defined as three-quarters of the value of the intercept (wall shear stress).

First-Stage Viscosity Trials

The objective of our first series of viscosity trials was to determine if the fluid carrier influences slurry viscosity.

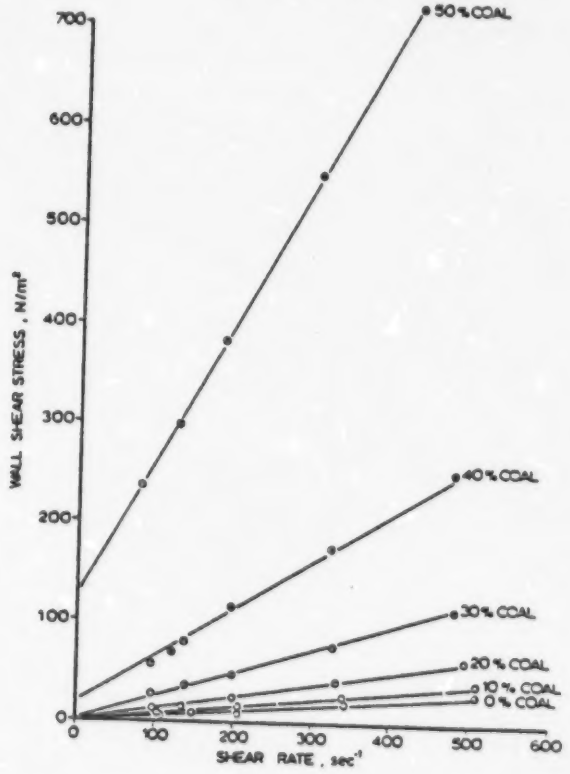
For this series of tests, we used five fluid carriers (No 6C oil, No 6P oil, tar, and tar with 10 and 20 percent additions of creosote) and minus 40 mesh Devco coal (Table I AVI). The Devco was added in 10 percent increments up to the limits of the mixer capability (40 percent with tar and 60 percent with No 6P oil).

Table I AVI: Minus 40 Mesh Devco Size Analysis

Tyler Mesh	Size Analysis	
	Weight %	Cumulative %
+10	0	0
+20	0.3	0.3
+35	2.5	2.8
+65	11.4	14.2
+100	12.4	26.6
+150	14.7	41.3
+200	24.0	65.3
-200	34.7	100

The results shown in figure 4 AVI for a No 6C oil-based slurry are typical for the slurries tested. As the coal concentration increases, the slurry changes from a Newtonian fluid to a Bingham Plastic.

Figure 4 AVI: Rheological Data for Minus 40 Mesh Devco in No 6C Oil at 185°F



The shear stress/shear rate relationships (figure 4 AVI) were found to be linear by standard regression techniques. For all cases, the intercept was tested to determine whether or not it was statistically different from zero. Slurries with intercepts statistically different from zero were classed as Bingham Plastics. This crude method of classifying slurries was considered adequate for our purposes.

In the Newtonian fluid cases, the slope of the line is the viscosity for all flow conditions. This number, μ, was divided by the base fluid viscosity, μ_o, to produce the dimensionless ratio μ/μ_o. In the Bingham Plastic case, the slope represents the viscosity at high (or infinite shear rates) and this number was divided by μ_o to produce the dimensionless viscosity. Finally, dimensionless kinematic viscosities (ν/ν_o) were calculated. Table II AVI gives the analysis of the slurries of figure 4 AVI (see also Tables VIII AVI to XV AVI).

Table II AVI: Rheological Data for Minus 40 Mesh Devco in No 6C Oil at 185°F

Coal Concentration		Slope $\left(1000\ \frac{N\cdot sec}{m^2}\right)$ (Cp)	Yield Stress (N/m^2)	Rheological Type	σ Slurry (gm/cm^3)	$\frac{\mu}{\mu_o}$	$\frac{\nu}{\nu_o} = \left(\frac{\mu/\rho}{\mu_o/\rho_o}\right)$
Wt %	Vol %						
0	0	66.8	0	N	0.9	1	1
10	6.9	86.8	0	N	0.93	1.30	1.26
20	14.3	131.8	0	N	0.96	1.97	1.85
30	22.2	228.8	0	N	1.0	3.43	3.09
40	30.8	510.5	7.2	BP	1.04	7.64	6.61
50	40.0	1473	85.5	BP	1.08	22.1	18.4

N = Newtonian
BP = Bingham Plastic

These data were analyzed by nonlinear regression methods to determine whether a unique curve could describe the behavior of all the systems studied.

The rheological behavior of these systems can be described by the equation:

$$\frac{\nu}{\nu_o} = k_1 e^{k_2 C^2} \qquad .....(2\ AVI)$$

where: C = coal concentration in volume percent
k_1 and k_2 = coefficients

This relationship is similar to that established in our previous studies; however, the No 6P oil-based slurries do not have the same coefficients as the other slurries.

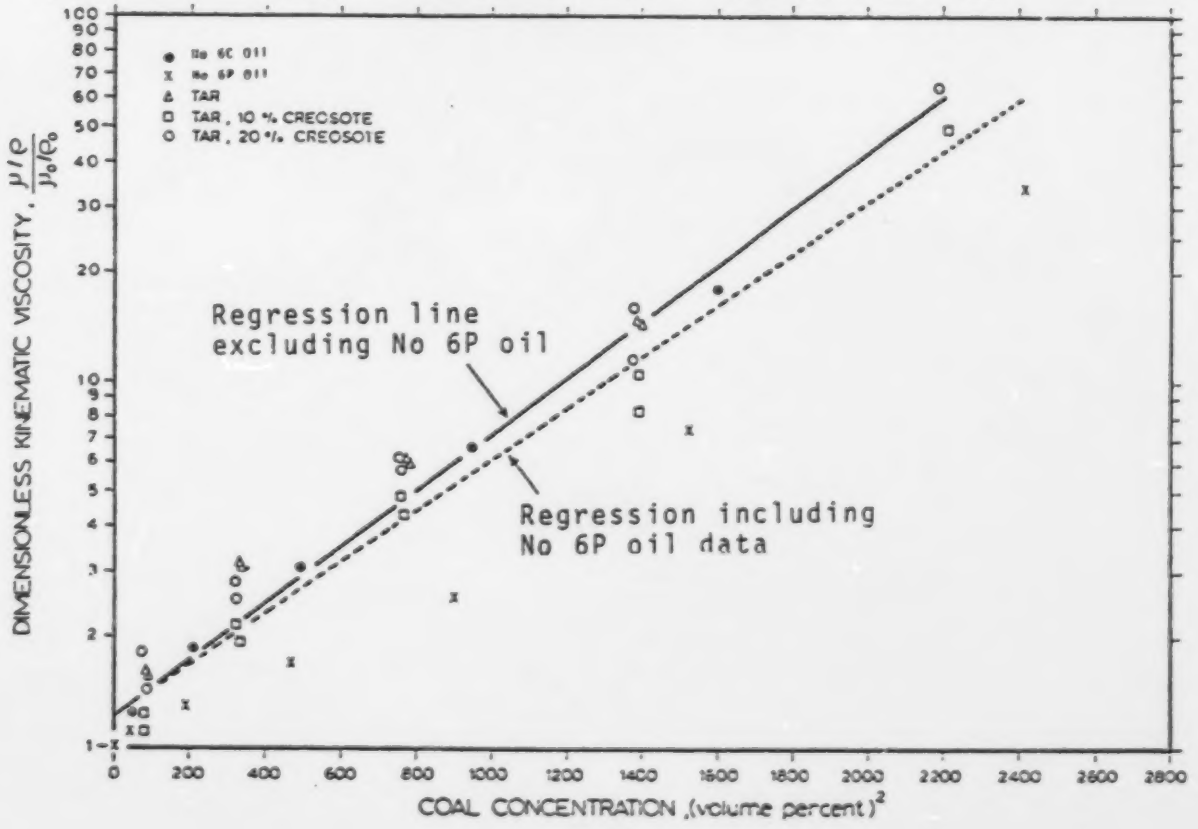
A second regression was performed on the data excluding the No 6P oil results. Exclusion of the No 6P oil results improved the model fit, particularly the coefficient of variation (Table III AVI).

Table III AVI: Nonlinear Regression Data for Slurries

Regression	Coefficients		R_2	F	$F_{(1,44)_{0.01}}$	Coefficient of Variation (%)
	K_1	K_2				
All Data	1.205	1.649 (10^{-3})	0.937	635	7.27	77.46
Excluding No 6P Oil	1.224	1.756 (10^{-3})	0.966	1035	7.27	16.77

The rheological behavior of the minus 40 mesh Devco slurries is shown in figure 5 AVI.

Figure 5 AVI: Rheological Behavior of Minus 40 Mesh Devco Slurries



The results of the first-stage viscosity trials suggested that carrier fluid affects slurry viscosity and that separate viscosity/concentration relationships might exist for each carrier fluid. In a second series of viscosity trials, we tried to further clarify the effect of carrier fluid as well as the effects of temperature and of coal size.

Second-Stage Viscosity Trials

For our second series of viscosity tests we examined slurries that we felt might be suitable for blast furnace injection. We planned to use slurries of similar composition for our combustion trials, which were to take place after the viscosity trials.

For these viscosity trials we used three size ranges of Devco coal (Table IV AVI) with three carrier fluids and two slurry temperatures (Table V AVI). Each slurry was tested twice.

Table IV AVI: Devco Size Distributions used for Second-Stage Viscosity Trials

Tyler Mesh	Coal Retained on Tyler Mesh					
	%	Cum %	%	Cum %	%	Cum %
+10	10.4	10.4				
+20	20.4	30.8				
+35	24.3	55.1	0.2	0.2		
+65	17.8	72.9	37.4	37.6		
+100					5.3	5.3
+150	12.1	85.0	29.1	66.7	9.7	15.0
+200					11.5	26.5
+270	6.4	91.4	14.3	81.0	6.0	32.5
-270	8.6	100.0	18.9	100.0	67.5	100.0
Product Designation	-10 mesh		-35 mesh		-100 mesh	

Table V AVI: Carrier Fluids and Test Temperatures

Fluid	Temperatures (°F)	
	Low	High
Tar	170	185
No 6C Oil	160	185
No 6P Oil	120	170

The data was treated in the same manner as for the first series of viscosity tests. The results are presented in Tables XVI AVI to XXXIII AVI. (Plots of the data resemble figure 4 AVI).

As a rule of thumb, we noted that slurries became non-Newtonian (exhibited a yield stress) for slurry kinematic viscosities greater than approximately 10 stokes.

Curvilinear regression analysis of the second-stage viscosity data produced equation 3 AVI as a correlation between dimensionless kinematic viscosity and coal concentration:

$$\frac{\nu}{\nu_o} = Ae^{(B_0 + B_1 + B_2 + B_3 + B_4)C^2} \qquad .....(3\ AVI)$$

$$\text{or} \quad \ln \frac{\nu}{\nu_o} = \ln A + (B_0 + B_1 + B_2 + B_3 + B_4)C^2 \qquad .....(4\ AVI)$$

where:

ν = slurry kinematic viscosity at temperature, T°F

ν_o = carrier fluid kinematic viscosity at temperature, T°F

A = intercept

C = coal concentration, volume percent

B_0 = effect of increasing the concentration of minus 10 mesh coal in tar

B_1 = additional effect of minus 35 mesh coal (over minus 10 mesh)

B_2 = additional effect of minus 100 mesh coal (over minus 10 mesh)

B_3 = additional effect of No 6C oil

B_4 = additional effect of No 6P oil

The values of A and B are listed in Table VI AVI and the correlation is graphically presented in figure 6 AVI. The regression statistics are listed in Table VII AVI.

Table VI AVI: Regression Coefficients

Coefficient	Value
A	1.1584
B_0	164.507 E-05
B_1	7.89354 E-05
B_2	29.6037 E-05
B_3	-42.0540 E-05
B_4	-49.4149 E-05

Figure 6 AVI: Slurry Viscosity

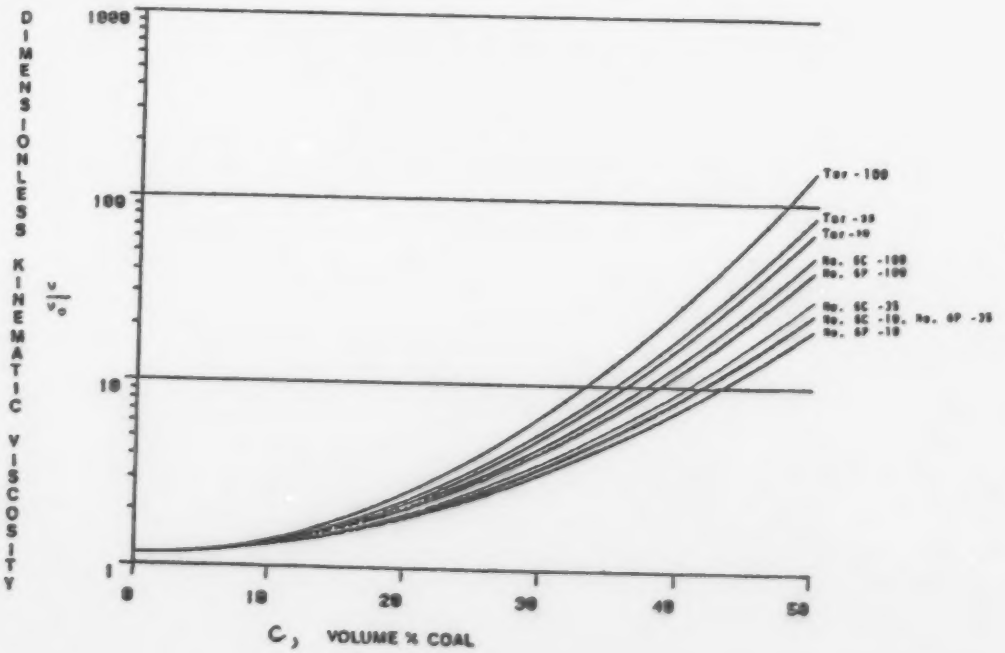


Table VII AVI: Regression Statistics

Statistic	R^2	F	$F(1,\infty)_{0.01}$	Coefficient of Variation (%)
Value	0.955	811	6.63	19.6

To use equation 4 AVI, select the proper combination of B values. For example, to compute the kinematic viscosity of a 50 wt percent of minus 100 mesh coal in No 6P oil slurry at 170°F, use B_0, B_2, and B_4 [the additional effect of minus 100 mesh coal (B_2) in No 6P oil (B_4) over that of minus 10 mesh coal in tar (B_0)]. Thus, equation 4 AVI would be:

$$\ln \frac{\nu}{\nu_o} = \ln 1.1584 + [(164.507 + 29.6037 - 49.4149)E\text{-}05]C^2$$

Values of ν_o and C are given in Tables VII AVI to XXXIII AVI (Tables XXII AVI for this particular case).

Additional Rheology Data

Tables VIII AVI to XXXIII AVI present the rheology data.

Table VIII AVI: Rheological Data for Minus 40 Mesh Devco in No 6C Oil at 185°F

Coal Concentration		Slope $\left(1000 \frac{N\cdot sec}{m^2}\right)$ (Cp)	Yield Stress (N/m^2)	Rheological Type	σ Slurry (gm/cm^3)	$\frac{\mu}{\mu_o}$	$\frac{\nu}{\nu_o} = \left(\frac{\mu/\rho}{\mu_o/\rho_o}\right)$
Wt %	Vol %						
0	0	66.8	0	N	0.9	1	1
10	6.9	86.8	0	N	0.93	1.30	1.26
20	14.3	131.8	0	N	0.96	1.97	1.85
30	22.2	228.8	0	N	1.0	3.43	3.09
40	30.8	510.5	7.2	BP	1.04	7.64	6.61
50	40.8	1473	85.5	BP	1.08	22.1	18.4

N = Newtonian
BP = Bingham Plastic

Table IX AVI: Rheological Data for Minus 40 Mesh Devco in No 6P Oil at 170°F

Coal Concentration		Slope $\left(1000 \frac{N \cdot sec}{m^2}\right)$ (Cp)	Yield Stress (N/m^2)	Rheological Type	σ Slurry (gm/cm^3)	$\frac{\mu}{\mu_o}$	$\frac{\nu}{\nu_o} = \left(\frac{\mu/\rho}{\mu_o/\rho_o}\right)$
Wt %	Vol %						
0	0	23.0	0	N	0.87	1	1
10	6.7	26.2	0	N	0.9	1.14	1.10
20	13.9	32.0	0	N	0.93	1.39	1.3
30	21.6	44.4	0	N	0.97	1.93	1.73
40	30.0	68.9	0	N	1.01	3.00	2.58
50	39.1	208.5	0	N	1.06	9.07	7.44
60	49.1	1099	32.5	BP	1.10	43.87	34.7

Table X AVI: Rheological Data for Minus 40 Mesh Devco in Tar at 170°F

Coal Concentration		Slope $\left(1000 \frac{N \cdot sec}{m^2}\right)$ (Cp)	Yield Stress (N/m^2)	Rheological Type	σ Slurry (gm/cm^3)	$\frac{\mu}{\mu_o}$	$\frac{\nu}{\nu_o} = \left(\frac{\mu/\rho}{\mu_o/\rho_o}\right)$
Wt %	Vol %						
0	0	185.1	0	N	1	1	1
10	9.0	299.8	0	N	1.22	1.62	1.61
20	18.3	601.1	0	N	1.23	3.25	3.20
30	27.7	1144	32.6	BP	1.25	6.18	5.98
40	37.4	2782	215.3	BP	1.26	15.05	14.5

Table XI AVI: Rheological Data for Minus 40 Mesh Devco in Tar at 185°F

Coal Concentration		Slope $\left(1000 \frac{N \cdot sec}{m^2}\right)$ (Cp)	Yield Stress (N/m^2)	Rheological Type	σ Slurry (gm/cm^3)	$\frac{\mu}{\mu_o}$	$\frac{\nu}{\nu_o} = \left(\frac{\mu/\rho}{\mu_o/\rho_o}\right)$
Wt %	Vol %						
0	0	118.9	0	N	1.20	1	1
10	9.0	186.6	0	N	1.21	1.57	1.56
20	18.2	392.5	0	N	1.23	3.30	3.22
30	27.6	742.4	116.6	BP	1.24	6.24	6.04
40	37.2	1916.6	103.2	BP	1.26	16.11	15.31

Table XII AVI: Rheological Data for Minus 40 Mesh Devco in Tar + 10 Percent Creosote at 170°F

Coal Concentration		Slope $\left(1000 \frac{N \cdot sec}{m^2}\right)$ (Cp)	Yield Stress (N/m^2)	Rheological Type	σ Slurry (gm/cm^3)	$\frac{\mu}{\mu_o}$	$\frac{\nu}{\nu_o} = \left(\frac{\mu/\rho}{\mu_o/\rho_o}\right)$
Wt %	Vol %						
0	0	177.2	0	N	1.20	1	1
10	9.0	220.4	0	N	1.22	1.24	1.22
20	18.2	345.5	0	N	1.23	1.95	1.90
30	27.6	795.5	0	N	1.24	4.49	4.35
40	37.3	1536	45.4	BP	1.26	8.67	8.46

Table XIII AVI: Rheological Data for Minus 40 Mesh Devco in Tar + 10 Percent Creosote at 185°F

Coal Concentration		Slope $\left(1000 \frac{N \cdot sec}{m^2}\right)$ (Cp)	Yield Stress (N/m^2)	Rheological Type	σ Slurry (gm/cm^3)	$\frac{\mu}{\mu_o}$	$\frac{\nu}{\nu_o} = \left(\frac{\mu/\rho}{\mu_o/\rho_o}\right)$
Wt %	Vol %						
0	0	105.8	0	N	1.20	1	1
10	9.0	117.5	0	N	1.21	1.11	1.10
20	18.1	227.8	0	N	1.22	2.12	2.09
30	27.5	537.0	0	N	1.24	5.08	4.92
40	37.2	1164	27.5	BP	1.25	11.0	10.6
50	47.0	5564	42.9	BP	1.27	52.41	49.5

Table XIV AVI: Rheological Data for Minus 40 Mesh Devco in Tar + 20 Percent Creosote at 170°F

Coal Concentration		Slope $\left(1000 \frac{N \cdot sec}{m^2}\right)$ (Cp)	Yield Stress (N/m^2)	Rheological Type	σ Slurry (gm/cm^3)	$\frac{\mu}{\mu_o}$	$\frac{\nu}{\nu_o} = \left(\frac{\mu/\rho}{\mu_o/\rho_o}\right)$
Wt %	Vol %						
0	0	106.6	0	N	1.20	1	1
10	9.0	153.0	0	N	1.21	1.44	1.43
20	18.1	272.6	0	N	1.22	2.56	2.52
30	27.5	642.8	0	N	1.24	6.03	5.83
40	37.1	1312	42.7	BP	1.25	12.13	11.6

Table XV AVI: Rheological Data for Minus 40 Mesh Devco in Tar + 20 Percent Creosote at 200°F

Coal Concentration		Slope $\left(1000 \frac{N \cdot sec}{m^2}\right)$ (Cp)	Yield Stress (N/m^2)	Rheological Type	σ Slurry (gm/cm^3)	$\frac{\mu}{\mu_o}$	$\frac{\nu}{\nu_o} = \left(\frac{\mu/\rho}{\mu_o/\rho_o}\right)$
Wt %	Vol %						
0	0	48.5	0	N	1.19	1	1
10	8.9	89.1	0	N	1.20	1.84	1.82
20	18.0	140.7	0	N	1.22	2.90	2.83
30	27.4	312.6	0	N	1.23	6.45	6.24
40	37.0	819.3	0	N	1.25	16.89	16.1
50	46.8	3352	100.5	BP	1.26	69.11	65.3

Table XVI AVI: Rheological Data for Minus 100 Mesh Devco in No 6C Oil at 160°F

Coal Concentration		Slope $\left(1000 \frac{N \cdot sec}{m^2}\right)$ (Cp)	Yield Stress (N/m^2)	Rheological Type	σ Slurry (gm/cm^3)	$\frac{\mu}{\mu_o}$	$\frac{\nu}{\nu_o} = \left(\frac{\mu/\rho}{\mu_o/\rho_o}\right)$
Wt %	Vol %						
0	0	94.2	0	N	0.91	1	1
10	7.0	137.3	0	N	0.94	1.46	1.41
30	22.4	393.4	0	N	1.01	4.18	3.76
50	40.3	2305	52.4	BP	1.09	24.47	20.43
0	0	131.5	0	N	0.91	1	1
10	7.0	210.6	0	N	0.94	1.60	1.55
30	22.4	366.9	0	N	1.01	2.79	2.51
40	31.0	726.4	0	N	1.05	5.52	4.79
45	35.6	1325	0	N	1.07	10.06	8.56
50	40.3	2131	0	N	1.09	16.21	13.53

Table XVII AVI: Rheological Data for Minus 100 Mesh Devco in No 6C Oil at 185°F

Coal Concentration		Slope $\left(1000 \frac{N \cdot sec}{m^2}\right)$ (Cp)	Yield Stress (N/m^2)	Rheological Type	σ Slurry (gm/cm^3)	$\frac{\mu}{\mu_o}$	$\frac{\nu}{\nu_o} = \left(\frac{\mu/\rho}{\mu_o/\rho_o}\right)$
Wt %	Vol %						
0	0	61.9	0	N	0.90	1	1
10	6.9	79.1	0	N	0.93	1.28	1.24
30	22.2	200.9	0	N	1.00	3.25	2.92
50	40.0	1535	7.5	BP	1.08	24.81	20.68
0	0	79.6	0	N	0.90	1	1
10	6.9	102.2	0	N	0.93	1.29	1.24
30	22.2	224.4	0	N	1.00	2.82	2.54
40	30.8	364.8	0	N	1.04	4.58	3.97
45	35.3	642.5	0	N	1.06	8.08	6.86
50	40.0	1162	15.7	BP	1.08	14.60	12.17

Table XVIII AVI: Rheological Data for Minus 35 Mesh Devco in No 6C Oil at 160°F

Coal Concentration		Slope $\left(1000 \frac{N \cdot sec}{m^2}\right)$ (Cp)	Yield Stress (N/m^2)	Rheological Type	σ Slurry (gm/cm^3)	$\frac{\mu}{\mu_o}$	$\frac{\nu}{\nu_o} = \left(\frac{\mu/\rho}{\mu_o/\rho_o}\right)$
Wt %	Vol %						
0	0	197.1	0	N	0.91	1	1
10	7.0	227.8	0	N	0.94	1.16	1.12
30	22.4	346.0	0	N	1.01	1.75	1.58
50	40.3	1090	22.2	BP	1.09	5.53	4.62
0	0	135.7	0	N	0.91	1	1
10	7.0	189.8	0	N	0.94	1.40	1.35
30	22.4	476.8	0	N	1.01	3.51	3.16
50	40.3	2007	24.8	BP	1.09	14.79	12.35
55	45.2	3254	69.2	BP	1.11	23.97	19.65
60	50.3	5213	237.8	BP	1.13	38.41	30.93

Table XIX AVI: Rheological Data for Minus 35 Mesh Devco in No 6C Oil at 185°F

Coal Concentration		Slope $\left(1000 \frac{N \cdot sec}{m^2}\right)$ (Cp)	Yield Stress (N/m^2)	Rheological Type	σ Slurry (gm/cm^3)	$\frac{\mu}{\mu_o}$	$\frac{\nu}{\nu_o} = \left(\frac{\mu/\rho}{\mu_o/\rho_o}\right)$
Wt %	Vol %						
0	0	101.1	0	N	0.90	1	1
10	6.9	11.09	0	N	0.93	1.10	1.06
30	22.2	191.9	0	N	1.00	1.90	1.71
50	40.0	655.6	6.5	BP	1.08	6.48	5.40
0	0	93.9	0	N	0.90	1	1
10	6.9	115.6	0	N	0.93	1.23	1.19
30	22.2	285.0	0	N	1.00	3.03	2.73
50	40.0	1088	0	N	1.08	11.59	9.66
55	44.9	2127	25.5	BP	1.10	22.65	18.53
60	50.0	4080	78.4	BP	1.13	43.45	34.61

Table XX AVI: Rheological Data for Minus 10 Mesh Devco in No 6C Oil at 160°F

Coal Concentration		Slope $\left(1000 \frac{N \cdot sec}{m^2}\right)$ (Cp)	Yield Stress (N/m^2)	Rheological Type	σ Slurry (gm/cm^3)	$\frac{\mu}{\mu_o}$	$\frac{\nu}{\nu_o} = \left(\frac{\mu/\rho}{\mu_o/\rho_o}\right)$
Wt %	Vol %						
0	0	130.8	0	N	0.91	1	1
10	7.0	157.1	0	N	0.94	1.20	1.16
30	22.4	368.4	0	N	1.01	2.81	2.53
50	40.3	1156	12.2	BP	1.09	8.82	7.36
0	0	168.1	0	N	0.91	1	1
10	7.0	169.4	0	N	0.94	1.01	0.98
30	22.4	389.5	0	N	1.01	2.32	2.09
35	26.6	445.5	0	N	1.03	2.65	2.34
40	31.0	654.8	0	N	1.05	3.90	3.38
45	35.6	736.8	0	N	1.07	4.39	3.73
50	40.3	1323	0	N	1.09	7.88	6.58
60	50.3	3103	50.7	BP	1.13	18.47	14.87

Table XXI AVI: Rheological Data for Minus 10 Mesh Devco in No 6C Oil at 185°F

Coal Concentration		Slope $\left(1000 \frac{N \cdot sec}{m^2}\right)$ (Cp)	Yield Stress (N/m^2)	Rheological Type	σ Slurry (gm/cm^3)	$\frac{\mu}{\mu_o}$	$\frac{\nu}{\nu_o} = \left(\frac{\mu/\rho}{\mu_o/\rho_o}\right)$
Wt %	Vol %						
0	0	59.5	0	N	0.90	1	1
10	6.9	77.1	0	N	0.93	1.28	1.24
30	22.2	189.1	0	N	1.00	3.15	2.84
50	40.0	606.2	7.4	BP	1.08	10.1	8.42
0	0	83.1	0	N	0.90	1	1
10	6.9	83.5	0	N	0.93	1.01	0.98
30	22.2	199.0	0	N	1.00	2.40	2.16
35	26.4	257.8	0	N	1.02	3.11	2.74
40	30.8	299.5	0	N	1.04	3.61	3.12
45	35.3	532.7	0	N	1.06	6.41	5.44
50	40.0	659.9	0	N	1.08	7.95	6.63
60	50.0	2144	0	N	1.13	25.83	20.57

Table XXII AVI: Rheological Data for Minus 100 Mesh Devco in No 6P Oil at 120°F

Coal Concentration		Slope $\left(1000 \frac{N \cdot sec}{m^2}\right)$ (Cp)	Yield Stress (N/m^2)	Rheological Type	σ Slurry (gm/cm^3)	$\frac{\mu}{\mu_o}$	$\frac{\nu}{\nu_o} = \left(\frac{\mu/\rho}{\mu_o/\rho_o}\right)$
Wt %	Vol %						
0	0	52.6	0	N	0.88	1	1
10	6.8	62.7	0	N	0.91	1.19	1.15
30	21.8	139.3	0	N	0.98	2.64	2.38
50	39.5	867.7	6.8	BP	1.07	16.50	13.57
60	49.4	3707	56.7	BP	1.11	70.50	55.89
0	0	65.8	0	N	0.88	1	1
10	0	84.1	0	N	0.91	1.28	1.24
30	21.8	142.0	0	N	0.98	2.16	1.94
50	39.5	894.0	0	N	1.07	13.57	11.16
55	44.3	696.4	0	N	1.09	10.58	8.54
60	49.4	3521	110.2	BP	1.11	53.51	42.42

Table XXIII AVI: Rheological Data for Minus 100 Mesh Devco in No 6P Oil at 170°F

Coal Concentration		Slope $\left(1000 \frac{N \cdot sec}{m^2}\right)$ (Cp)	Yield Stress (N/m^2)	Rheological Type	σ Slurry (gm/cm^3)	$\frac{\mu}{\mu_o}$	$\frac{\nu}{\nu_o} = \left(\frac{\mu/\rho}{\mu_o/\rho_o}\right)$
Wt %	Vol %						
0	0	19.7	0	N	0.87	1	1
10	6.7	24.1	0	N	0.90	1.22	1.18
30	21.6	40.0	0	N	0.97	2.02	1.82
50	39.1	338.4	0	N	1.06	17.15	14.08
60	49.1	1845	13.0	BP	1.10	93.38	73.86
0	0	28.5	0	N	0.87	1	1
10	6.7	29.1	0	N	0.90	1.02	0.99
30	21.6	47.4	0	N	0.97	1.66	1.49
50	39.1	305.3	0	N	1.06	10.71	8.79
55	44.0	1669	37.7	BP	1.08	58.56	47.17
60	49.1	1393	25.7	BP	1.10	48.88	38.66

Table XXIV AVI: Rheological Data for Minus 35 Mesh Devco in No 6P Oil at 120°F

Coal Concentration		Slope $\left(1000 \frac{N \cdot sec}{m^2}\right)$ (Cp)	Yield Stress (N/m^2)	Rheological Type	σ Slurry (gm/cm^3)	$\frac{\mu}{\mu_o}$	$\frac{\nu}{\nu_o} = \left(\frac{\mu / \rho}{\mu_o / \rho_o}\right)$
Wt %	Vol %						
0	0	87.1	0	N	0.88	1	1
10	6.8	103.6	0	N	0.91	1.19	1.15
30	21.8	199.4	0	N	0.98	2.29	2.06
50	39.5	730.4	0	N	1.07	8.39	6.90
0	0	70.2	0	N	0.88	1	1
10	6.8	89.0	0	N	0.91	1.27	1.23
30	21.8	116.0	0	N	0.98	1.65	1.48
50	39.5	659.1	0	N	1.07	9.39	7.72
55	44.3	1275	16.8	BP	1.09	18.15	14.65
60	49.4	2170	86.6	BP	1.11	30.90	24.50

Table XXV AVI: Rheological Data for Minus 35 Mesh Devco in No 6P Oil at 170°F

Coal Concentration		Slope $\left(1000 \frac{N \cdot sec}{m^2}\right)$ (Cp)	Yield Stress (N/m^2)	Rheological Type	σ Slurry (gm/cm^3)	$\frac{\mu}{\mu_o}$	$\frac{\nu}{\nu_o} = \left(\frac{\mu / \rho}{\mu_o / \rho_o}\right)$
Wt %	Vol %						
0	0	29.0	0	N	0.87	1	1
10	6.7	32.1	0	N	0.90	1.11	1.07
30	21.6	57.9	0	N	0.97	2.00	1.79
50	39.1	276.6	0	N	1.06	9.55	7.84
70	60.0	2167	248.4	BP	1.16	74.89	56.09
0	0	25.9	0	N	0.87	1	1
10	6.7	21.2	0	N	0.90	0.82	0.79
30	21.6	52.8	0	N	0.97	2.04	1.83
50	39.1	254	0	N	1.06	9.83	8.06
55	44.0	511.0	0	N	1.08	19.75	15.91
60	49.1	1077	0	N	1.10	41.61	32.91
70	60.0	8735	332	BP	1.16	337	253

Table XXVI AVI: Rheological Data for Minus 10 Mesh Devco in No 6P Oil at 120°F

Coal Concentration		Slope $\left(1000 \frac{N \cdot sec}{m^2}\right)$ (Cp)	Yield Stress (N/m^2)	Rheological Type	σ Slurry (gm/cm^3)	$\frac{\mu}{\mu_o}$	$\frac{\nu}{\nu_o} = \left(\frac{\mu/\rho}{\mu_o/\rho_o}\right)$
Wt %	Vol %						
0	0	24.1	0	N	0.87	1	1
10	6.7	20.9	0	N	0.90	0.88	0.85
30	21.6	37.4	0	N	0.97	1.54	1.38
50	39.1	156.9	0	N	1.06	6.54	5.37
60	49.1	361.4	0	N	1.10	15.04	11.79
0	0	20.4	0	N	0.87	1	1
10	6.7	22.9	0	N	0.90	1.12	1.09
30	21.6	41.8	0	N	0.97	2.05	1.84
50	39.1	190.7	0	N	1.06	9.35	7.67
55	44.0	288.0	0	N	1.08	14.12	11.37
60	49.1	455.5	0	N	1.10	22.33	17.66
Rheological Data for -10 Mesh Devco in No 6P Oil at 200°F							
70	59.7	1277	30.2	BP	1.15	-	-

Table XXVII AVI: Rheological Data for Minus 10 Mesh Devco in No 6P Oil at 170°F

Coal Concentration		Slope $\left(1000 \frac{N \cdot sec}{m^2}\right)$ (Cp)	Yield Stress (N/m^2)	Rheological Type	σ Slurry (gm/cm^3)	$\frac{\mu}{\mu_o}$	$\frac{\nu}{\nu_o} = \left(\frac{\mu/\rho}{\mu_o/\rho_o}\right)$
Wt %	Vol %						
0	0	60.7	0	N	0.88	1	1
10	6.8	66.3	0	N	0.91	1.08	1.04
30	21.8	128.1	0	N	0.98	2.10	1.89
50	39.5	453.4	0	N	1.07	7.43	6.11
60	49.4	987.0	21.8	BP	1.11	16.18	12.83
0	0	61.7	0	N	0.88	1	1
10	6.8	87.1	0	N	0.91	1.40	1.35
30	21.8	152.7	0	N	0.98	2.47	2.22
50	39.5	513.7	0	N	1.07	8.29	6.82
55	44.3	689.2	0	N	1.09	11.11	8.97
60	49.4	1489	15.2	N	1.11	24.02	19.04

Table XXVIII AVI: Rheological Data for Minus 100 Mesh Devco in Tar at 170°F

Coal Concentration		Slope $\left(1000 \frac{N \cdot sec}{m^2}\right)$ (Cp)	Yield Stress (N/m^2)	Rheological Type	σ Slurry (gm/cm^3)	$\frac{\mu}{\mu_o}$	$\frac{\nu}{\nu_o} = \left(\frac{\mu/\rho}{\mu_o/\rho_o}\right)$
Wt %	Vol %						
0	0	50.2	0	N	1.21	1	1
10	9.1	70.3	0	N	1.22	1.40	1.39
30	27.8	334.0	0	N	1.25	6.66	6.45
0	0	66.3	0	N	1.21	1	1
10	9.1	127.3	0	N	1.22	1.92	1.90
25	23.0	349.1	0	N	1.24	5.26	5.14
30	27.8	568.5	0	N	1.25	8.57	8.30
35	32.6	625.6	0	N	1.26	9.43	9.06
40	37.4	1774	12.8	BP	1.26	26.74	25.68

Table XXIX AVI: Rheological Data for Minus 100 Mesh Devco in Tar at 185°F

Coal Concentration		Slope $\left(1000 \frac{N \cdot sec}{m^2}\right)$ (Cp)	Yield Stress (N/m^2)	Rheological Type	σ Slurry (gm/cm^3)	$\frac{\mu}{\mu_o}$	$\frac{\nu}{\nu_o} = \left(\frac{\mu/\rho}{\mu_o/\rho_o}\right)$
Wt %	Vol %						
0	0	38.0	0	N	1.20	1	1
10	9.0	60.9	0	N	1.21	1.60	1.59
30	27.6	225.9	0	N	1.24	5.94	5.75
50	47.1	3272	92.6	BP	1.27	86.08	81.34
0	0	44.4	0	N	1.20	1	1
10	9.0	84.0	0	N	1.21	1.89	1.87
25	22.9	263.0	0	N	1.23	5.92	5.78
30	27.6	400.4	0	N	1.24	9.01	8.72
35	32.4	946.2	0	N	1.25	21.30	20.44
40	37.2	1148	13.5	BP	1.26	25.84	24.61

Table XXX AVI: Rheological Data for Minus 35 Mesh Devco in Tar at 170°F

Coal Concentration		Slope $\left(1000 \frac{N \cdot sec}{m^2}\right)$ (Cp)	Yield Stress (N/m^2)	Rheological Type	σ Slurry (gm/cm^3)	$\frac{\mu}{\mu_o}$	$\frac{\nu}{\nu_o} = \left(\frac{\mu/\rho}{\mu_o/\rho_o}\right)$
Wt %	Vol %						
0	0	151.6	0	N	1.21	1	1
10	9.1	247.6	0	N	1.22	1.63	1.62
20	18.3	394.4	0	N	1.24	26.0	2.54
25	23.0	617.8	0	N	1.24	4.08	3.98
30	27.8	986.0	0	N	1.25	6.50	6.30
40	37.4	1966	0	N	1.26	12.97	12.45
50	47.3	5615	69.6	BP	1.28	37.04	35.01
0	0	69.8	0	N	1.21	1	1
10	9.1	135.3	0	N	1.22	1.94	1.92
25	23.0	321.6	0	N	1.24	4.61	4.50
30	27.8	444.8	0	N	1.25	6.37	6.17
35	32.6	684.3	0	N	1.26	9.80	9.42
40	37.4	1176	0	N	1.26	16.85	16.18
50	47.3	2817	195.2	BP	1.28	40.37	38.17

Table XXXI AVI: Rheological Data for Minus 35 Mesh Devco in Tar at 185°F

Coal Concentration		Slope $\left(1000 \frac{N \cdot sec}{m^2}\right)$ (Cp)	Yield Stress (N/m^2)	Rheological Type	σ Slurry (gm/cm^3)	$\frac{\mu}{\mu_o}$	$\frac{\nu}{\nu_o} = \left(\frac{\mu/\rho}{\mu_o/\rho_o}\right)$
Wt %	Vol %						
0	0	104.7	0	N	1.20	1	1
10	9.0	158.0	0	N	1.21	1.51	1.50
20	18.2	315.4	0	N	1.23	3.01	2.94
25	22.9	390.2	6.0	BP	1.23	3.73	3.64
30	27.6	476.9	20.4	BP	1.24	4.55	4.41
40	37.2	1120	18.8	BP	1.26	10.70	10.19
50	47.1	3195	48.9	BP	1.27	30.53	28.84
0	0	58.7	0	N	1.20	1	1
10	9.0	99.4	0	N	1.21	1.69	1.68
25	22.9	250.0	0	N	1.23	4.24	4.14
30	27.6	229.3	0	N	1.24	3.91	3.78
35	32.4	537.3	0	N	1.25	9.16	8.79
40	37.2	741.4	0	N	1.26	12.64	12.04
50	47.1	2191	97.1	BP	1.27	37.35	35.29

Table XXXII AVI: Rheological Data for Minus 10 Mesh Devco in Tar at 170°F

Coal Concentration		Slope $\left(1000 \frac{N \cdot sec}{m^2}\right)$ (Cp)	Yield Stress (N/m^2)	Rheological Type	σ Slurry (gm/cm^3)	$\frac{\mu}{\mu_o}$	$\frac{\nu}{\nu_o} = \left(\frac{\mu/\rho}{\mu_o/\rho_o}\right)$
Wt %	Vol %						
0	0	231.1	0	N	1.21	1	1
10	9.1	391.1	0	N	1.22	1.69	1.68
30	27.8	860.1	0	N	1.25	3.72	3.60
40	37.4	1902	59.6	BP	1.26	8.23	7.90
0	0	124.5	0	N	1.21	1	1
10	9.1	152.9	0	N	1.22	1.22	1.21
20	18.3	292.1	0	N	1.24	2.34	2.28
25	23.0	351.4	0	N	1.24	2.81	2.74
30	27.8	559.2	0	N	1.25	4.47	4.33
40	37.4	940.8	0	N	1.26	7.53	7.23

Table XXXIII AVI: Rheological Data for Minus 10 Mesh Devco in Tar at 185°F

Coal Concentration		Slope $\left(1000 \frac{N \cdot sec}{m^2}\right)$ (Cp)	Yield Stress (N/m^2)	Rheological Type	σ Slurry (gm/cm^3)	$\frac{\mu}{\mu_o}$	$\frac{\nu}{\nu_o} = \left(\frac{\mu/\rho}{\mu_o/\rho_o}\right)$
Wt %	Vol %						
0	0	78.4	0	N	1.20	1	1
10	9.0	104.9	0	N	1.21	1.35	1.34
20	18.2	205.4	0	N	1.23	2.63	2.57
25	22.9	217.2	0	N	1.23	2.78	2.71
30	27.6	345.3	0	N	1.24	4.42	4.28
40	37.2	654.4	0	N	1.26	8.38	7.98

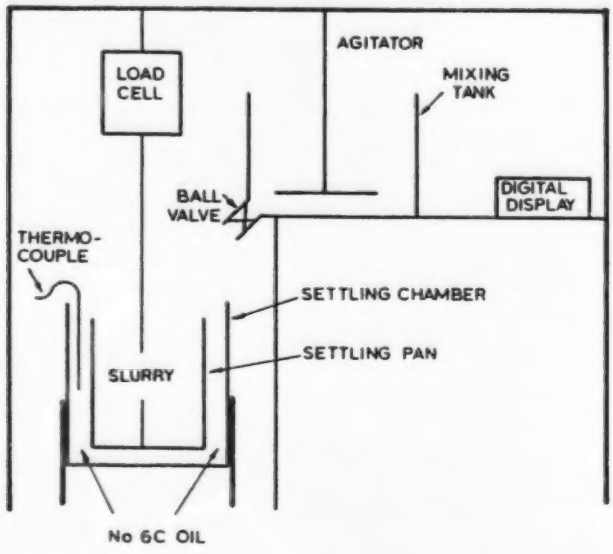
APPENDIX VII

STABILITY TEST

Slurry Settling Apparatus and Test Procedure

Figure 1 AVII is a schematic representation of the test apparatus.

Figure 1 AVII: Test Apparatus



In the upper mixing tank, the slurry was agitated to ensure homogeneity at the correct temperature. The slurry was then emptied rapidly, via a ball valve, into the lower steam-heated settling chamber. In the settling chamber was a wide, high-walled settling pan located near the chamber bottom and suspended from a load cell.

At the start of each test the settling pan floated on pure carrier fluid in the settling chamber. As slurry filled the pan it sank into the carrier fluid. The carrier fluid rose and filled the space between the pan and chamber walls, reaching the top of the pan's walls at the same time as the slurry filling the

inside of the pan. Slurry was added to a height 2in above the submerged pan. Thus, a small quantity of coal settled between the pan and chamber walls. We do not feel that this settling coal affected the results. Initially, the entire chamber and pan were filled with slurry, but the coal settling between the walls and below the pan affected the results.

The settling pan was of diameter and height such that 90 percent of the entering slurry was caught. The accumulating weight of the coal (Table I AVII) settling on the pan was recorded continuously by filming the digital display of the load cell readout with a video tape unit containing an integral timer.

Table I AVII: Devco Size Analysis (Stability Tests)

Tyler Mesh	Size Analysis	
	Weight %	Cumulative %
+10	5.6	5.6
+20	16.4	22.0
+35	24.0	46.0
+65	20.6	66.6
+150	15.0	81.6
+270	7.4	89.0
-270	11.0	100.0

The recorded weights were accurate to 0.05 pound and the slurry weight was about 50 pounds. Settling data is given in Tables II AVII to VII AVII.

Table II AVII: Settling of 10 Wt % Coal in No 6C Oil

Weight of Settled Coal (lb)	Elapsed Time (min)
0.05	0.07
0.10	0.15
0.15	0.54
0.20	1.37
0.25	2.94
0.30	3.88
0.33	9.10

Table III AVII: Settling of 20 Wt % Coal in No 6C Oil

Weight of Settled Coal (lb)	Elapsed Time (min)
0.10	0.16
0.20	1.03
0.30	2.55
0.40	5.50
0.50	10.70
0.60	26.68
0.63	44.00

Table IV AVII: Settling of 30 Wt % Coal in No 6C Oil

Weight of Settled Coal (lb)	Elapsed Time (min)
0.10	0.15
0.20	0.65
0.30	1.93
0.40	3.53
0.50	5.95
0.60	9.57
0.70	16.72
0.80	31.86
0.90	57.28

Table V AVII: Setting of 40 Wt % Coal in No 6C Oil

Weight of Settled Coal (lb)	Elapsed Time (min)
0.10	0.07
0.20	1.35
0.30	2.66
0.40	4.47
0.50	9.86
0.60	19.96
0.70	27.67
0.80	31.45
0.90	42.32
1.00	64.35
1.10	78.93
1.20	87.12
1.25	100.00

Table VI AVII: Settling of 50 Wt % Coal in No 6C Oil

Weight of Settled Coal (lb)	Elapsed Time (min)
0.10	2.05
0.20	7.70
0.30	13.94
0.40	24.55
0.50	35.38
0.60	43.22
0.70	61.88
0.80	67.85
0.90	79.98
1.00	86.43
1.10	90.03
1.20	97.34
1.30	104.01
1.40	113.01
1.50	128.01
1.60	139.01
1.70	151.01
1.75	161.01

Table VII AVII: Settling of 40 Wt % Coal in No 6P Oil

Weight of Settled Coal (lb)	Elapsed Time (min)
0.10	0.07
0.20	0.12
0.30	0.24
0.40	0.36
0.50	0.55
0.60	0.78
0.70	1.06
0.80	1.50
0.90	2.19
1.00	2.96
1.10	3.64
1.20	4.47
1.30	5.52
1.40	6.72
1.50	8.00
1.60	9.84
1.70	11.93
1.80	14.41
1.90	17.22
2.00	21.82
2.10	28.46
2.20	41.43
2.25	55.38

To determine the effects of coal size and of slurry stabilizers, we allowed slurries of 40 wt percent of coal in No 6C oil to settle for approximately 1 hr. The slurry in the top half of the settling pan was removed and extracted the oil fraction by Soxhlet extraction with hot toluene. The recovered coal was dried and dry screened. Data for these tests is listed in Tables VIII AVII to XIV AVII. The procedures used for the stabilizers are summarized in Table XV AVII.

Table VIII AVII: Settling in Unstabilized Slurries

Test No 1		Test No 2	
Weight of Settled Coal (lb)	Elapsed Time (min)	Weight of Settled Coal (lb)	Elapsed Time (min)
0.10	0.10	0.10	0.05
0.20	0.24	0.20	0.07
0.30	0.39	0.30	0.17
0.40	0.96	0.40	0.55
0.60	5.83	0.60	3.10
0.70	8.29	0.70	6.81
0.80	17.20	0.80	22.50
0.85	22.82	0.90	32.46

Table IX AVII: Settling in a Slurry Stabilized with Emulsified Water

Weight of Settled Coal (lb)	Elapsed Time (min)
0.10	0.28
0.20	0.49
0.30	0.99
0.40	1.90
0.50	3.59
0.60	6.32
0.70	15.03
0.80	40.63

Table X AVII: Settling in a Slurry Stabilized with Alchem BX 1797

Weight of Settled Coal (lb)	Elapsed Time (min)
0.10	0.13
0.20	0.23
0.30	0.36
0.40	0.56
0.50	0.98
0.60	2.41
0.70	5.11
0.80	13.50
0.90	24.03

Table XI AVII: Settling in a Slurry Stabilized with Drew Amergy 5200

Weight of Settled Coal (lb)	Elapsed Time (min)
0.10	0.02
0.20	0.16
0.30	0.41
0.40	0.59
0.50	0.88
0.60	1.42
0.70	2.73
0.80	5.02
0.90	13.32
0.95	27.54

Table XII AVII: Settling in a Slurry Stabilized with Quaker City Cat-Ionic SCB

Weight of Settled Coal (lb)	Elapsed Time (min)
0.10	0.14
0.20	0.34
0.30	0.75
0.40	2.36
0.50	7.16
0.60	12.51
0.70	26.01
0.80	36.30
0.90	56.07

Table XIII AVII: Settling in a Slurry Stabilized with Quaker City Non-Ionic SCA

Weight of Settled Coal (lb)	Elapsed Time (min)
0.10	0.05
0.20	0.15
0.30	0.31
0.40	0.54
0.50	1.12
0.60	2.00
0.70	3.87
0.80	23.18

Table XIV AVII: Size Analysis of Coal Suspended in Top Half of Settling Chamber

Tyler Mesh	Weight of Coal (g)						
	Unstabilized		Stabilized				
	No 1	No 2	Non-Ionic SCA	Cat-Ionic SCB	Amergy 5200	Water-in-Oil Emulsion	BX 1797
+65	0.1	0.1	2.2	0.1	0.4	0.2	0.3
-65 +150	0.7	0.4	17.7	5.5	3.8	2.4	1.6
-150 +270	9.1	8.0	15.4	20.2	18.6	24.2	14.7
-270	41.8	42.7	24.2	59.9	52.7	55.2	55.5

Table XV AVII: Stabilizer Addition

Stabilizer	Quantity (Wt % of Oil)	Method of Addition
Quaker City Non-Ionic SCA Quaker City Cat-Ionic SCB Drew Amergy 5200 Alchem BX 1797	0.3	The chemicals were first added to water (5 wt % of oil). The solution was emulsified in oil using an ORF HydroShear. The coal was added to the stabilizer/water/oil emulsion.
Emulsified Water	5.0	The water was emulsified in oil using an ORF HydroShear. The coal was added to the emulsion.